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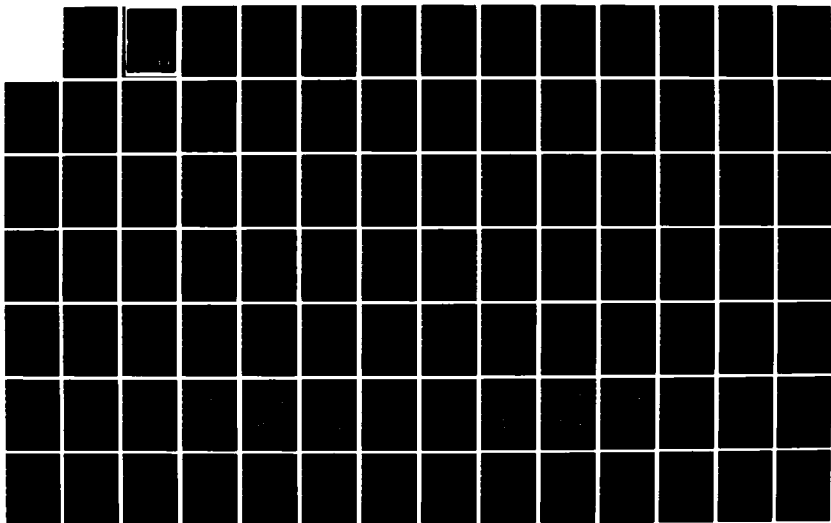
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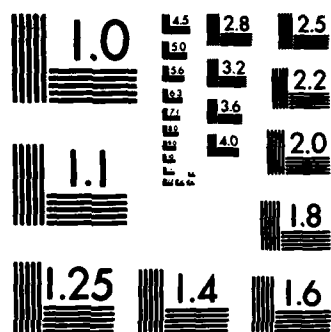
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SECRET

AD-A151 605

1. REF

AFIT/CI/NR 85-5D

2. ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)

A Statistical Method For One-To Three-Day
Tropical Cyclone Track Prediction

5. TYPE OF REPORT & PERIOD COVERED

THESIS/DISSERTATION

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

Clifford R. Matsumoto

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS

AFIT STUDENT AT: Colorado State Univ

10. PROGRAM ELEMENT, PROJECT, TASK
AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS

AFIT/NR
WPAFB OH 45433

12. REPORT DATE

1984

13. NUMBER OF PAGES

200

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)

UNCLASS

16. DECLASSIFICATION/DOWNGRADING
SCHEDULE

17. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

18. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

19. SUPPLEMENTARY NOTES

APPROVED FOR PUBLIC RELEASE: IAW AFR 100-1

Lynn E. Wolaver
 LYNN E. WOLAVER 28 Feb 85
 Dean for Research and
 Professional Development
 AFIT, Wright-Patterson AFB OH

20. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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EDITION OF 1 NOV 65 IS OBSOLETE

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85 03 11 070

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A STATISTICAL METHOD FOR ONE-TO THREE-DAY
TROPICAL CYCLONE TRACK PREDICTION

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The problem of forecasting the movement of tropical cyclones is crucial in many parts of the world. Progress on improving the accuracy of track prediction has been slow to come and the need for further research on statistical-synoptic approaches exists. This newly developed method of forecasting one- to three-day cyclone motion is an improvement over existing forecast schemes for the following reasons:

(1) cyclones are stratified based on their positions relative to the 500 mb subtropical ridge to better define the environmental influences on the cyclones; (2) the 72-hour forecast track is segmented into three 24-hour time steps to permit the application of updated persistence and synoptic data relative to each new cyclone position as the 24-hour displacements are stepped forward to the desired forecast projection; and (3) the prognostic synoptic data are introduced only at their valid times and relative to the cyclone position at the valid time such that they are treated like analysis data.

A screening -- multiple regression technique is used with the "perfect-prog" concept to introduce numerically forecast synoptic data in the development of the regression coefficients. Actual forecast fields are used to test the skill of the new model to be referred to as CSU84.

Comparison with operational forecast techniques on a nearly homogeneous sample using a persistence-climatology model as a normalizer to indicate relative skill of the models as compared to a no-skill forecast indicate that CSU84 is six times as skillful as the best operational model in the Atlantic and at least four times as skillful as the best operational model in the northwest Pacific. These very encouraging verification results suggest the potential for significant reduction in forecast position errors and should hasten the testing of the model in an operational environment.

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Fall 1984

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DISSERTATION

A STATISTICAL METHOD FOR ONE-TO THREE-DAY TROPICAL
CYCLONE TRACK PREDICTION

Submitted by

Clifford R. Matsumoto

Department of Atmospheric Science

In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 1984

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Fort Collins, Colorado

Fall 1984

COLORADO STATE UNIVERSITY

September 21, 1984

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION
BY Clifford R. Matsumoto
ENTITLED A Statistical Method for One-to Three-Day Tropical Cyclone
Track Prediction
BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF
Doctor of Philosophy

Committee on Graduate Work

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ACKNOWLEDGEMENTS

The author is indebted to Professor William M. Gray for his support and encouragement of this operationally oriented research topic. The author also profited from extensive discussion with Jianmin Xu of the China Central Meteorological Agency, Beijing. Jianmin Xu was a visiting scientist on Professor Gray's research project from 1980 to 1982. Gratitude is also expressed to Ms. Barbara Brumit, Patti Nimmo, and Cindy Schrandt for their invaluable help in manuscript preparation and drafting. And, of course, none of this would have been possible without the patience and understanding of my wife, Frances.

This research was performed while the author was a graduate student with the support of the U.S. Air Force. It has been financially supported jointly by the National Science Foundation/National Oceanic and Atmospheric Administration Grant No. ATM-8214041 and by the Naval Environmental Prediction Research Facility Grant No. N00014-83-K-0002. Acknowledgement is made to the National Center for Atmospheric Research, which is sponsored by the National Science Foundation, for the extensive computing resources necessary to accomplish this research.

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LIST OF SYMBOLS AND ACRONYMS

BPAC	<u>B</u> lended <u>P</u> ersistence <u>A</u> nd <u>C</u> limatology forecast aid for the NW Pacific and North Indian Oceans
C_o	the intercept value for the regression equation
C_n	the n regression coefficients
CLIM	<u>CL</u> IMatology forecast aid for the NW Paific and North Indian Oceans
CLIPER	<u>CL</u> IMatology and <u>P</u> ERsistence forecast system for the Atlantic (Neumann, 1972)
COSMOS	<u>C</u> yclops <u>O</u> bjective <u>S</u> teering <u>M</u> odel <u>O</u> utput <u>S</u> tatistics forecast aid at JTWC (Allen, 1984)
CYCLOPS	<u>CY</u> CLone <u>O</u> perational <u>P</u> rediction <u>S</u> ystem forecast model for the NW Pacific
CY50	<u>CY</u> clops forecast model that uses <u>500</u> mb steering for the NW Pacific and North Indian Ocean
DOM	direction of motion
E_c	CLIPER forecast error
E_m	model forecast error
FLAT	forecast latitude
FLON	forecast longitude
FNOC	<u>F</u> leet <u>N</u> umerical <u>O</u> ceanography <u>C</u> enter, Monterey, CA
H	500 mb geopotential height
HOURL	12 or 24 hours for computing displacement
HP	500 mb height pattern indicator
HPAC	<u>H</u> alf <u>P</u> ersistence <u>A</u> nd <u>C</u> limatology forecast aid for the NW Pacific and North Indian Ocean

HATTRACK Hurricane And Typhoon TRACKing forecast aid for the NW Pacific and North Indian Oceans (Renard, 1968)

HURRAN HURRricane ANalog forecast system for the Atlantic (Hope and Neumann, 1970)

JTWC Joint Typhoon Warning Center, Guam

LAT_o current latitude

LAT_p previous latitude either 12 or 24 hours earlier

LON_o current longitude

LON_p previous longitude either 12 or 24 hours earlier

m meter

mb millibar

m/s meter per second

MFM Movable Fine Mesh dynamical model (Hovermale and Livezey, 1977)

MOHATT MODified HATTrack forecast aid for the NW Pacific and North Indian Ocean (Renard et al., 1973)

MOS Model Output Statistics

n number of predictors for a given regression equation

P_n the n predictor values

NCAR National Center for Atmospheric Research, Boulder, CO

NEPRF Naval Environmental Prediction Research Facility

NEWLAT forecast latitude

NEWLON forecast longitude

NHC National Hurricane Center, Miami, FL

NHC67 NHC statistical-synoptic forecast system (Miller, et al., 1968)

NHC72 NHC statistical-synoptic forecast system (Neumann, et al., 1972)

NHC73 NHC statistical-dynamical forecast system (Neumann and Lawrence, 1973)

NMC National Meteorological Center, Washington, D.C.

NTCM	<u>N</u> avy <u>T</u> wo-Way <u>I</u> nteractive <u>T</u> ropical <u>C</u> yclone <u>M</u> odel for the NW Pacific and North Indian Ocean (Harrison, 1981)
OLDLAT	forecast minus 24-hour latitude
OLDLON	forecast minus 24-hour longitude
OTCM	<u>O</u> ne-Way <u>I</u> nteractive <u>T</u> ropical <u>C</u> yclone <u>M</u> odel for the NW Pacific and North Indian Ocean (Hodur and Burk, 1978)
SANBAR	<u>S</u> ANders <u>B</u> ARotropic model for the Atlantic (Sanders and Burpee, 1968)
T	time
TYAN	<u>T</u> Yphoon <u>A</u> Nalog forecast system for the NW Pacific and North Indian Ocean (Jarrell and Somerville, 1970)
P	Sea level Pressure
SMOS	<u>S</u> imulated <u>M</u> odel <u>O</u> utput <u>S</u> tatistics
XLAT	best track latitude
XLON	best track longitude
XTRP	<u>E</u> XTRA <u>P</u> olation forecast aid for the NW Pacific and North Indian Oceans
Σ	summation
x	multiplication
X	east-west displacement
Y	north-south displacement
S	cyclone speed in m/sec
φ	gradient of geopotential height
φ	latitude
Ω	angular speed of rotation of the earth
Δ	delta
U	east-west component of the geostrophic steering wind/east-west cyclone motion
V	north-south component of the geostrophic steering wind north-south cyclone motion

ΔH	24-hour change of height
ΔP	24-hour change of sea level pressure
Δq	24-hour change of height gradient
%	percent improvement or deterioration of model skill over CLIPER forecast error

1. INTRODUCTION

The problem of forecasting the movement of tropical cyclones, particularly recurvature and landfall, is crucial in many parts of the world. Considerable effort has been expended by the various Meteorological Services of a number of nations on improving the accuracy of track prediction. A historical overview will be presented in Chapter 2.

Although significant progress has been made in developing statistical and dynamical models for forecasting the tracks of tropical cyclones, the forecast errors over the last few years (Fig. 1.1) have shown little improvement. The official forecasts for the NW Pacific issued by the US Joint Typhoon Warning Center (JTWC) on Guam have average forecast position errors on the order of 120, 240, and 360 nautical miles (n mi.) for 24-, 48-, and 72-hour forecasts while those for the North Atlantic issued by the US National Hurricane Center (NHC) in Miami have errors on the order of 120, 250, and 380 n mi.

Attempts to develop more sophisticated numerical models continue in hopes of achieving a breakthrough in track prediction. However, the achievement of this goal does not appear to be close at hand. In addition, in most developing countries, computer facilities are not adequate to apply the more sophisticated dynamical models. Therefore, the need remains for a tropical cyclone forecasting technique requiring only meteorological data from a network of conventional surface and upper-air observing stations as basic input.

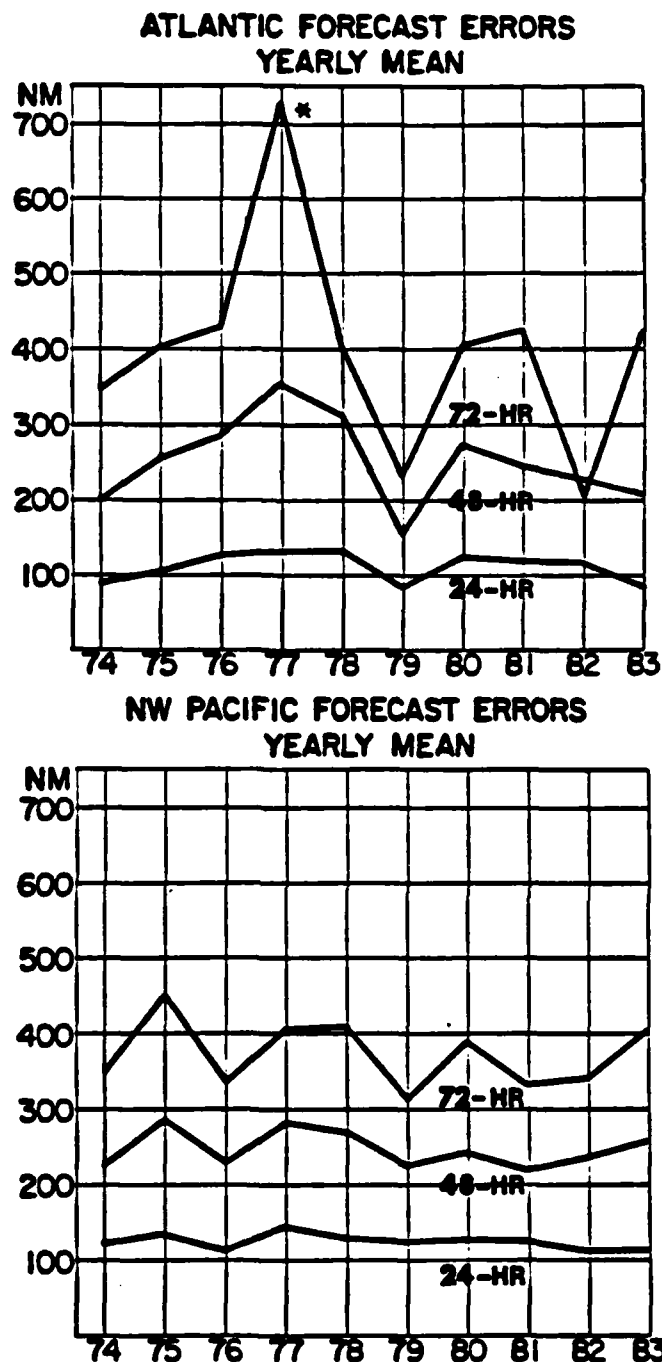


Fig. 1.1. The yearly mean official forecast errors (n mi.) during the period 1974-1983 for the Atlantic and NW Pacific. The yearly fluctuation is much higher in the Atlantic than the NW Pacific due to far fewer cases. In 1977, for example, there were only two cases for verification at 72 hours. The 1974-1982 errors for the Atlantic are from Annual Data and Verification Tabulation while the 1983 errors are from the minutes of the 38th Annual International Hurricane Conference. The errors for the NW Pacific are from the Annual Tropical Cyclone Typhoon Reports, 1974-1983.

Furthermore, a review of objective techniques currently in operational use reveals inherent weaknesses in their design. These weaknesses will be specifically addressed in Chapter 3.

The purpose of this research was to apply a new statistical method of introducing synoptic and persistence predictors to develop an improved prediction model that could be used at all operational forecast centers. Such a model would need to be simple so that it could operate without a link to a large computer data base or numerically produced analysis or forecast fields, yet be sophisticated enough to produce accurate forecasts at both the short and longer forecast periods.

The motivation for this work arose as a result of nearly three years of operational tropical cyclone forecasting by the author during which time the strengths and weaknesses of the myriad of objective techniques in use became obvious. Almost all of these track prediction schemes perform adequately on well-behaved cyclones that follow climatological tracks. However, on those anomalous, difficult cases when the forecaster needs objective guidance the most, the schemes invariably fail.

In developing a new and improved statistical forecast model, the method of introducing and applying the various climatological, persistence and synoptic predictors for predicting the future motion of tropical cyclones is patterned after the normal procedure followed by most forecasters as they subjectively formulate the forecast track.

The innovative approach developed here primarily involves the discretizing of the 72-hour forecast track into three 24-hour time steps and applying updated persistence and synoptic data relative to each new cyclone position as the forecast is stepped forward in 24-hour

increments. The perfect-prog method is used to introduce the updated synoptic information but only at the valid time of the prognostic data and always relative to the cyclone position at the valid time of the prognostic data. Climatology is incorporated via a stratification scheme based on the position of the cyclone relative to the 500 mb subtropical ridge. Segmenting the 72-hour cyclone motion permits the category the cyclone is in to change after each 24 hours of motion, if necessary. The three categories relative to the ridge -- south, on, north -- result in three sets of regression equations with one set comprised of equations for the north-south and east-west displacements. A more detailed discussion of the model designs will be presented in Chapter 3.

Chapter 4 will discuss the multiple regression technique used to handle the large number of cases and potential predictors. Correlation coefficient fields between the synoptic predictors and east-west and north-south cyclone motion will be presented along with an examination of the contribution of each of the predictors to the reduction of variance.

Results from the verification of this new statistical prediction model, to be referred to as CSU84, will be presented in Chapter 5. Also presented in this chapter will be sensitivity tests that simulate operational conditions. This was accomplished by perturbing the "best track",⁽¹⁾ initial positions and by using actual forecast fields produced by a numerical model.

(1) The best track positions are the accepted cyclone positions after a post-cyclone analysis.

Although CSU84 was initially an attempt to improve track forecasts primarily at the higher latitudes and at the longer forecast periods, the results indicate considerable skill at the lower latitudes and shorter forecast periods as well.

2. BACKGROUND

The movements of tropical cyclones remain one of the most important and difficult forecasting problems in tropical meteorology. Earliest attempts at developing objective forecast schemes hypothesized that tropical cyclones were carried along by the prevailing larger scale environmental flows in which they were embedded like eddies in a river. This concept has come to be known as ''steering''.

More recently, observational studies have demonstrated a highly significant relationship between tropical cyclone motion and synoptic-scale flow (~ 500 - 1000 km) around the cyclone. The pressure level at which the speed and direction of the surrounding winds (or equivalently the pressure or height gradients across the cyclone) best correlate with those of the cyclone has been referred to as the steering level.

One problem in applying the steering concept has been the selection of the proper level that best correlated with the movement of the cyclone. Although different forecast schemes use different steering levels, it is generally accepted that the mid-tropospheric levels are the best in predicting tropical cyclone movement.

George (1975) found that for NW Pacific cyclones, the composite 500 mb winds averaged between 1 - 7° latitude radius from the cyclone center had the strongest correlation with the direction of cyclone movement while the 700 mb winds best correlated with the cyclone speed. Gray (1977) presented similar results for Atlantic cyclones. Chan (1982) using composite wind data over an area $(5$ - 7° latitude radius from the

cyclone center) outside the strong inner circulation of the cyclone found that the winds at the mid-troposphere (700, 600 and 500 mb) correlated best with both the direction and speed of cyclone movement. More importantly, Chan found that cyclones having different zonal components of motion have different relationships with their $5-7^{\circ}$ surrounding flow. Holland (1983) showed that cyclone motion was the result of a nonlinear combination of two processes: 1) an interaction between the cyclone and its basic current (the well-known steering concept), and 2) an interaction with the earth's vorticity field which causes a westward deviation from the pure steering flow. Similar to Chan's findings, Holland discovered that westward moving cyclones were only marginally affected by fluctuations in the basic flow whereas northward and eastward moving cyclones may undergo large motion changes for a similar range of fluctuations.

Attempts to use winds and heights at upper tropospheric levels (e.g., Jordan, 1952; Miller, 1958) have historically not been as successful and have received little use. However, recent findings have supported a good correlation between upper tropospheric winds and the recurvature phenomenon. Specifically, George and Gray (1977), using 10 years of composited rawinsonde reports, found large-scale differences at the 200 mb level 15° to 20° from the cyclone prior to significant changes in cyclone movement. Their results indicated that the strength of the upper level westerlies northwest and north of the cyclone is strongly related to whether a cyclone recurved or not.

Bao and Sadler (1982) also found a strong relationship between the 200 mb winds at and before recurvature along the cyclone's subsequent track and the speed of movement of the cyclone after recurvature.

Gentry (1983) found that when the mean 200 mb winds at about 15° to 20° northwest and north of the cyclone equal or exceed 20 m/s that 80% of the cyclones recurved before traveling as much as 12 degrees of longitude further west.

Weir (1982) developed an operational technique for the NW Pacific using 200 mb winds to assist in forecasting the acceleration of typhoons as they interact with the mid-latitude westerlies.

Apparently, upper tropospheric levels are generally poor steering levels with the exception of recurving cyclones. The reason for this observed peculiarity is perhaps due to the greater 200-500 mb directional shear in the deep tropics. With recurving cyclones, on the other hand, directional shear is much less and the 200 mb winds provide an extra degree of predictive information for cyclones interacting with the mid-latitude westerlies.

The surface-pressure map together with 24-hour surface-pressure changes (to eliminate large diurnal effects in the tropics) has been used by tropical cyclone forecast centers since the 1950's. It is still used in conjunction with more sophisticated techniques to better assess the shorter range objective forecasts versus the current synoptic situation. In addition, pressure changes outside the cyclone's circulation have been used to indicate future changes in motion. When there are large pressure changes far removed from the cyclone, their effect is to turn the cyclone at right angles to the line connecting the isallobaric center and the cyclone center.

A new prediction model was developed with the purpose of assimilating all of these observations linking cyclone motion to various synoptic scale flow. Specifically, all cyclones were stratified

relative to the 500 mb subtropical ridge to incorporate the findings of Chan (1982), Xu and Gray (1982), Holland (1983) and others indicating different steering relationships for cyclones having different zonal components of motion or different locations relative to the ridge. Further, 200 mb steering predictors were used 0-20° northwest and north of the cyclone based on the correlation between upper tropospheric winds and recurvature shown by the numerous studies just cited. Five hundred millibar heights and surface pressures and their 24-hour changes were used as predictors to assess the current and recent changes in the synoptic situation at two different levels. The use of 200 mb steering winds provided a third vertical level. Seventy-two hours of cyclone motion were segmented into three shorter 24-hour time steps and forecast fields relative to each new cyclone position were used to better define the synoptic flow and its changes affecting the movement of the cyclone as it evolved over a 3-day period.

Based on the steering concept just mentioned, a number of other tropical cyclone track forecasting schemes have been developed to relate statistically or dynamically cyclone motion to the surrounding flow field. A review of the basic categories of objective techniques used for predicting tropical cyclone motion and a general summary of the major tropical cyclone track prediction methods developed over the years will now be presented.

There are four basic categories of objective techniques used for predicting tropical cyclone motion:

- (1) climatology-persistence
- (2) steering flow
- (3) statistical
- (4) numerical

Appendix A presents the various techniques currently in operational use in the Atlantic and the NW Pacific/North Indian Oceans. A more detailed discussion of these track prediction models can be found in Neumann and Peilissier (1981) for the Atlantic and in the Annual Tropical Cyclone Report prepared by the Joint Typhoon Warning Center (JTWC) for the other ocean basins.

2.1 Climatology-Persistence Methods

Climatology-persistence methods rely upon empirical relationships related to the tracks of previous cyclones or the past motion of the current cyclone. These techniques are useful for well-behaved cyclones that move along a climatological track with few changes in direction. Because most cyclones in the deep tropics embedded in the easterlies exhibit this type of motion, climatology-persistence methods perform well for cyclones at low latitudes. But these techniques break down in the westerly wind belt regions.

2.2 Steering Flow Method

The steering flow concept views the tropical cyclone as point vortices embedded in the basic environmental flow and being moved by the steering current. Observations support this concept of the cyclone responding to the environmental flow in which it is embedded.

Difficulty of applying this concept operationally occurs when the data does not allow proper steering definition or when vertical shear in the environmental flow is present and there is doubt as to which level is the optimum steering level.

2.3 Statistical Method

The statistical approach compares different parameters or combinations of parameters quantitatively to cyclone motion. Multiple

regression analysis is employed to develop correlation coefficients and regression equations.

As summarized by Neumann (1979), statistical models for predicting tropical cyclone motion can be grouped into two broad categories: those models based on analog and those based on regression equations. The latter, in order of increasing sophistication, can be further categorized as follows:

- (a) Those models which use predictors based on climatology and persistence;
- (b) Those models which include, but which are not limited to, predictors derived from observed synoptic data;
- (c) Those models which include, but which are not limited to predictors (a) and (b), but also include predictors derived from numerically-forecast data.

The models that fall into category (c) are known as statistical/dynamical models while those that fall into categories (a) and (b) have been referred to respectively as simulated analog models and classical or statistical-synoptic models.

2.3.1 Analog Models

2.3.1.1 The Analog Concept

Analog models derive their success from their ability to identify families of cyclone tracks. Using a series of computer algorithms, a current cyclone is associated with its most likely family, thus allowing inferences to be made about its future motion. The analog process identifies historical cyclones temporally and spatially similar to the current cyclone. Typically, such factors as time of year, the cyclone's initial direction of motion and speed and the position of the analog

cyclone relative to the current cyclone are considered. Selected analog tracks, translated to a common origin, and combined with persistence, make up the final forecast. Refinements over the years have included analog weighting schemes, use of past as well as current motion and better combinations of climatology and persistence.

2.3.1.2 Historical Development

The first fully operational model for predicting tropical cyclone motion by analog methods was developed by Hope and Neumann (1970) for use by the US National Hurricane Center (NHC) on Atlantic cyclones. The technique, known by the acronym HURRAN (HURRicane ANalog), has been in continuous use at the Center since the beginning of the 1969 hurricane season.

Concurrently and independently, Hodge and McKay (1970) collaborated with the US Navy and developed an analog prediction model for North Pacific typhoons. Their model, known as TYFOON, was revised by Jarrell and Somerville (1970) and became operational at the Joint Typhoon Warning Center, Guam in August 1970.

Following the introduction of HURRAN and TYFOON, and their moderate success, the analog concept became quite popular. The HURRAN/TYFOON system was adopted and modified for use in the North Indian Ocean, southwest Indian Ocean, northeastern Pacific and in the southwest Pacific and Australian area.

2.3.1.3 Advantages and Disadvantages of the Analog Method

The main advantage of the analog is its simplicity and economy in terms of computer resources. It is quick to run and is one of the first objective guidances available to the forecaster. In addition, the method is very accurate for cyclones in the deep tropics embedded in the

easterlies since analog forecasts represent typical or normal cyclone motion and deviations from normal in the tropics are small.

However, at higher latitudes where cyclones are affected by the westerlies, anomalous situations are much more common and analog forecasts are more unreliable. Neumann and Hope (1972) have found that about one out of three forecast situations in the Atlantic is too anomalous for an analog method to arrive at a solution.

Another disadvantage of the analog method is a forecast bias introduced when cyclones are prematurely dropped from the history tape due to landfall, extratropical transition or dissipation. In these instances, the forecast is excessively influenced by the remaining cyclone tracks.

2.3.2 Regression Equation Models

2.3.2.1 Historical Development

The first of the statistical systems for tropical cyclone track forecasting was developed by Riehl, et al. (1956) using the geostrophic wind components computed from the 500 mb heights around the periphery of the cyclone as a method of representing the vertically integrated steering flow. Miller and Moore (1960) calculated additional geostrophic wind components for steering at the 700 and 300 mb levels as well as the past movement of the cyclone as predictors. Arakawa (1964) and Tse (1966) developed a similar method for use in the Pacific as did Kumar and Prasad (1973) for the North Indian Ocean. The Tse method is somewhat unique in that one of five sets of regression equations were used, depending on which one of five easily identifiable 700 mb patterns existed.

All of these methods used a relatively small grid surrounding the cyclone to forecast 24-hour cyclone motion. However, because of their sensitivity to the initial analysis, all suffer from the subjectivity of uncertain analysis close to the cyclone center.

Veigas, et al. (1959) were the first to apply screening - multiple linear regression statistical methods to the problem of tropical cyclone forecasting. Rather than restrict potential predictors to the cyclone vicinity, Veigas used a large storm-centered grid to introduce predictors that represented large-scale weather patterns. This method had the advantage of being less sensitive to the initial analysis near the cyclone.

A major advance in statistical prediction of tropical cyclone motion occurred with the development of the NHC64 system. In this scheme, Miller and Chase (1966) combined the better features of the Veigas, Miller-Moore and Riehl-Haggard methods into a single model.

Sea level pressures, 700 mb heights and 500 mb heights as well as 1000-700 mb thicknesses, 700-500 mb thicknesses, 500 mb height changes, geostrophic wind components at the 1000 mb, 700 mb and 500 mb levels and the past 12-hour movement of the cyclone center were used as predictors. Cyclones greater than 34 kts for the period 1945-1961 formed the development set which was divided into two classes - north and south of 27.5°N . A screening-multiple linear regression technique was used to derive four sets of equations -- one set for the 0-12 hour north-south and east-west displacements, a second set for the 12-24 hour displacements, a third set for the 24-36 hour displacements and a fourth set for the 36-48 hour displacements. Forecasts for periods greater than 12 hours were prepared by adding forecast displacements for

successive periods. A 48-72 hour forecast was added to the technique later.

As a result of NHC64's poor performance on an erratic cyclone (Betsy) in 1966, a new statistical model was developed (Miller, et al., 1968). The revised model, known as NHC67, is still in use at the National Hurricane Center in Miami. Data from hurricanes during the years 1962-1965 were added to the 1945-1961 period used in deriving the NHC64 equations. Additional predictors were screened in developing the NHC67 equations. These additional predictors were the 1000 mb heights (in place of sea level pressure), 1000 and 700 mb 24-hour height changes and the thermal winds computed from the thicknesses. Although equations to make the 48-72 hour forecast were derived due to the operational requirement to issue 72-hour forecasts, it was felt that these equations were of questionable value.

In order to provide an analog forecast as input to a higher echelon prediction model quickly and under any anomalous synoptic condition, Neumann (1972) developed a rather simple regression equation model for the Atlantic area known by the acronym CLIPER (CLImatology and PERsistence). Operational use of this improved analog model confirmed that climatology and persistence were being better used than by earlier models for cyclones embedded in the easterlies. However, when cyclones recurved out of the tropics, the analog models were still inferior to older models such as NHC67 which were cognizant of environmental flow patterns. Accordingly, Neumann, et al. (1972) blended the better features of both approaches into a new model for the Atlantic area known as NHC72.

However, Atlantic cyclones that exhibited anomalous motion continued to confirm the inherent inability of the purely "classical" models typified by NHC67 and NHC72 to forecast such motion. This finally resulted in the development of the so-called statistical/dynamical (as well as the purely dynamical) models which conceptually should respond better to anomalous synoptic conditions. Such models use the output from a numerical model as one set of predictors for input. Neumann and Lawrence (1973) used selected predictors from the 24-, 36-, and 48-hour prognostic 500 mb geopotential height fields produced by the US National Meteorological Center (NMC) Primitive Equation (PE) model for their statistical/dynamical NHC73 model. A great deal of success was achieved by NHC73, primarily on the longer-range forecasts. Another statistical/dynamical model developed by Nomoto, et al. (1976) is being used by the Japan Meteorological Agency on NW Pacific typhoons in the vicinity of Japan.

The term statistical/dynamical can also be applied to the HATTRACK (Hurricane And Typhoon-TRACKing) (Renard, 1968) and the MOHATT (Modified HATTrack) (Renard, et al., 1973) techniques used by JTWC on Guam. Instead of regression equations, tropical cyclones are geostrophically steered in six-hourly time steps using the US Navy's smoothed numerical prognoses at various levels (1000 mb, 850 mb, 700 mb, 500 mb, 400 mb, and 200 mb). The operational forecasts starting at time T_0 are based on a forecast cycle starting at time T_0 minus 12 hours. This allows for an error measurement of the motion for the first 12 hours of an 84-hour projection. This error, assumed to be a bias, is linearly applied with certain constraints, to the remaining 72-hour forecast track. The

operational version of HATTRACK/MOHATT is known by the acronym CYCLOPS (CYCLone Operational Prediction System).

Since 1983, a model output statistic technique known by the acronym COSMOS (Cyclops Objective Steering Model Output Statistics) (Allen, 1984) has been in operational use at JTWC, Guam, to assist the forecaster in interpreting the output from CYCLOPS. COSMOS uses the CYCLOPS forecasts at the 850, 700, and 500 mb levels to produce its own forecast based on a statistical analysis of the past performance of CYCLOPS.

2.3.2.2 Advantages and Disadvantages of the "Classical" Models

Several models in this category are in current operational use at the various tropical cyclone forecast centers. These include Arakawa's (1964) and Tse's (1966) models in the NW Pacific; Kumar and Prasad's (1973) model in the North Indian Ocean; and the North Atlantic NHC67 (Miller, et al., 1968) and NHC72 (Neumann, et al., 1972) models. All of these models incorporate predictors obtained from current or recently observed synoptic data to forecast future positions of the cyclone out to as much as 72 hours.

The reduction of variance of such models typically decreases rapidly with increased forecast projection. Predictors are selected from climatology and persistence as well as one or more of the current and 24-hour old 1000, 700, and 500 mb height fields. In fact, persistence provides most of the reduction of variance for the shorter-term forecast.

Separate sets of regression equations (stratification) representing different synoptic patterns have been developed for some of these models. Tse's (1966) model stratifies according to five easily

identifiable 700 mb patterns. The NHC67 model stratifies according to the cyclone's initial location north or south of 27.5°N with an additional substratification dependent on the cyclone's speed. A stratification based on the cyclone's initial motion is used by the NHC72 model.

Both the NHC67 and the NHC72 (as well as the NHC73) models use predictors from three levels -- 1000, 700, and 500 mb. According to Neumann (1979), tests conducted at the NHC subsequent to the development of these models suggest that better operational performance may be possible by the elimination of the 700 mb data. Data at this level are highly correlated with the 500 mb level and it appears that the models use more predictors than warranted by the sample size.

2.3.2.3 Advantages and Disadvantages of the Statistical-Dynamical Models

At the top of the statistical models for the prediction of tropical cyclone motion are those models which derive a portion of the variance reduction from predictors taken from the output of a numerical prediction model. Such models also derive a portion of their forecast skill from other sources such as climatology, persistence or current synoptic data.

The use of Model Output Statistics (MOS) is conceptually the most effective method of introducing numerically forecast data into a statistical prediction model. However, the lack of adequate data sample prevents the direct introduction of a numerical model output into a statistical model. As a result, substitute methods of using the statistical-dynamical approach have been derived. One of these is referred to as the "perfect-prog" approach and a second as the

Simulated Model Output Statistics (SMOS). The perfect-prog approach was used in the development of the model described in this paper.

In the perfect-prog method, observed values of a predictor at time $T_0 + \Delta T$ are used to derive a statistical relationship between predictor and predictand at the same time $T_0 + \Delta T$. In actual practice, forecast values of the predictor must be used and, therefore, any forecast error or bias is passed on to the statistical model. This is one reason why there is a tendency for the predictive skill of statistical-dynamical models developed using the perfect-prog method to degrade significantly when used operationally. With the MOS technique, the biases of the numerical model would have been statistically corrected and certain inaccuracies recognized.

In the SMOS method, the covariance matrices containing the sums and cross-products of all possible combinations of variable pairs are modified or "contaminated" by introducing an error component similar to that of actual prognostic data. The purpose of the contamination is to partially correct the tendency for the screening program to over-weight or select too many predictors from the perfect-prog data at the expense of the other potential predictors.

As discussed in Neumann and Lawrence (1973), NHC73 was tested on operational independent data using different sets of regression equations developed from the two methods. Both versions performed well at the extended forecast periods. As expected, the perfect-prog equations performed relatively poorly during the first half of the 72-hour forecast period. Predictor over-weighting was assumed to be the probable explanation. The improvement in the perfect-prog forecasts at the extended periods suggested that the variance reducing potential of

the numerically forecast data is greater than that provided by the current data at 48 hours and beyond.

The better operational performance of the SMOS equations for the shorter range forecast periods was believed to be the more realistic blend of current and numerically forecast data as a result of the contamination of the perfect-prog predictors.

In Japan, a statistical-dynamical model described by Nomoto, et al. (1976) is also designed around the perfect-prog concept. Its synoptic predictors come only from numerically produced 24-hour 500 mb prognostic geopotential height fields. With additional persistence predictors, the model provides 12-, 24-, 36-, and 48-hour forecast positions. With the exception of the HATTRACK/MOHATT version called CYCLOPS, there are no statistical-synoptic schemes of any kind in operational use in the NW Pacific or North Indian Oceans as of this date.

2.4 Numerical Method

Numerical models "appear" to provide the best promise for improvement in track forecasting. Dynamical techniques assume that the motion of the cyclone may be forecast directly from numerical integration of geophysical governing equations such as momentum, continuity and thermodynamics.

2.4.1 Historical Development

Harrison (1973) developed a simple nested grid model to forecast typhoon motion in the NW Pacific using the primitive equations. This is the original version of the nested two-way interactive tropical cyclone model (NTCM) in operational use at JTWC on Guam (Harrison, 1981). Prior to the development of the operational version of NTCM, a more simple version of the model without the fine grid was adapted for use in 1975.

This coarse-mesh (2°), three-layer dry model initially possessed boundary conditions which were insulated, free slip walls on the north and south and cyclic on the east and west. Hodur and Burk (1978) modified the "channel" model by incorporating one-way interactive boundaries with forecast fields from a global/hemispheric PE model providing the boundary values in 12 hour intervals. This modification, along with the adjustment of the initial wind fields near the center based on the difference between the actual and predicted cyclone motion after 6 hours using a technique developed by Shewchuk and Elsberry (1978), are incorporated in the current operational model known as OTCM. The NTCM and the OTCM are two of the better objective techniques at JTWC providing fairly accurate overall track prediction.

In the Atlantic, the SANBAR barotropic model (Sanders and Burpee, 1968) was developed on the belief that momentum advection is the primary physical mechanism for motion of intense tropical cyclones and that the cyclone is steered by the large-scale environmental flow in which it is embedded. Accordingly, the model uses a deep-layer (1000 - 100 mb) pressure - weighted U and V wind field analysis over the grid domain of the model. In the version of the model used operationally at the NHC, a technique described by Pike (1972) is used to modify the wind field near the cyclone to make it conform better to the initial cyclone motion vector. This technique is similar to one developed later by Shewchuk and Elsberry (1978) for use on the OTCM for the NW Pacific.

A baroclinic Movable Fine Mesh (MFM) dynamical model (Hovermale and Livezey, 1977) at the NHC was first tested operationally on Atlantic tropical cyclones during the 1975 season and has been in operational use since 1976. The MFM has far more resolution in the vertical (10 layers)

than the NTCM or the OTCM and also includes parameterization of cumulus convection and the planetary boundary layer as well as topography. A fine grid of 60 km is used over its entire domain.

The NTCM and OTCM, on the other hand, have only three vertical layers and use a simple analytic heating scheme with no topography. The finer scale of the NTCM (41 km grid) moves with the cyclone within a coarser channel model with grid spacing of 205 km. Once initialized, the model runs independently of any forecast fields. By contrast, the boundary conditions of both the MFM and OTCM are externally specified by forecast fields from the NMC spectral global model and FNOC spectral global model, respectively.

2.4.2 Advantages and Disadvantages of Numerical Models

Since a dynamical model does not depend on the statistical relationships between a current cyclone and historical cyclones, the reliability of the model could be expected to be independent of the details of a cyclone's past behavior. Thus, variations in the future track of a cyclone ought to be implicitly predicted through the equations of motion.

However, due to uncertain initial analyses, principally in and around the cyclone vortex, all dynamical models are noted for poor performance at the shorter forecast period and an overall motion that is too slow. They do demonstrate increased skill for the longer forecast periods beyond 36 hours. This observation has been noted by Fiorino, et al. (1982) for the NTCM and Neumann and Pelissier (1981) for the MFM. In an effort to improve the accuracy at the shorter forecast period, both the OTCM and SANBAR incorporate a biasing technique that forces the initial cyclone motion in the model to match the observed motion of the actual

cyclone. A similar bias-corrector technique is envisioned for the NTCM. Thus, the model is no longer independent of the cyclone's past behavior which is touted as one of the numerical model's strong points.

In addition, the NTCM is initialized from the operational FNOC global band tropical analysis fields. Since the analysis contains a mixture of observations, observed climatology and persistence, in data-sparse areas the cyclone track will probably have a significant climatological component.

The disadvantage of the complex and resource costly MFM is that computer resource limitations preclude any more than a 48 hour forecast, and then only under certain high threat conditions. Further, guidance from an MFM run is not available until approximately eight hours after synoptic time. Both the NTCM and OTCM, due to their relative simplicity, are run routinely to 72 hours twice a day on all tropical storms and typhoons. Their quick turnaround puts the model output at the disposal of the forecaster at the same time as he receives guidance from the other objective aids.

2.5 The Forecasting Dilemma

The error statistics over the years suggest that no one objective technique performs better than all others on every cyclone. Some schemes work well for some cyclones but poorly on others. This is one of the reasons for the myriad of forecast aids in operational use. An obvious problem of having too many techniques for objective guidance is illustrated in Fig. 2.1 where a typical "shotgun" effect makes it difficult for the forecaster to select the best forecast track. Such a scatter in the forecast track is common when a large directional change, as in recurvature, occurs. Note that the two numerical models (NTCM and

OTCM) and COSMOS, which applies MOS technique to the output from a purely steering scheme at three vertical levels, performed superior to the other aids. The superior performance of the dynamical models over the past five years for the NW Pacific and NHC73 for the Atlantic north zone indicates the importance of synoptic data, particularly in a prognostic sense, in any attempt to forecast cyclone motion.

However, the lack of observational data, initialization schemes that disregard certain observational data in favor of climatology, and the imperfect physics involved with PE models combine to bring about inaccurate analysis and prognostic fields. If the forecaster was able to modify these fields when they were obviously in error an improved

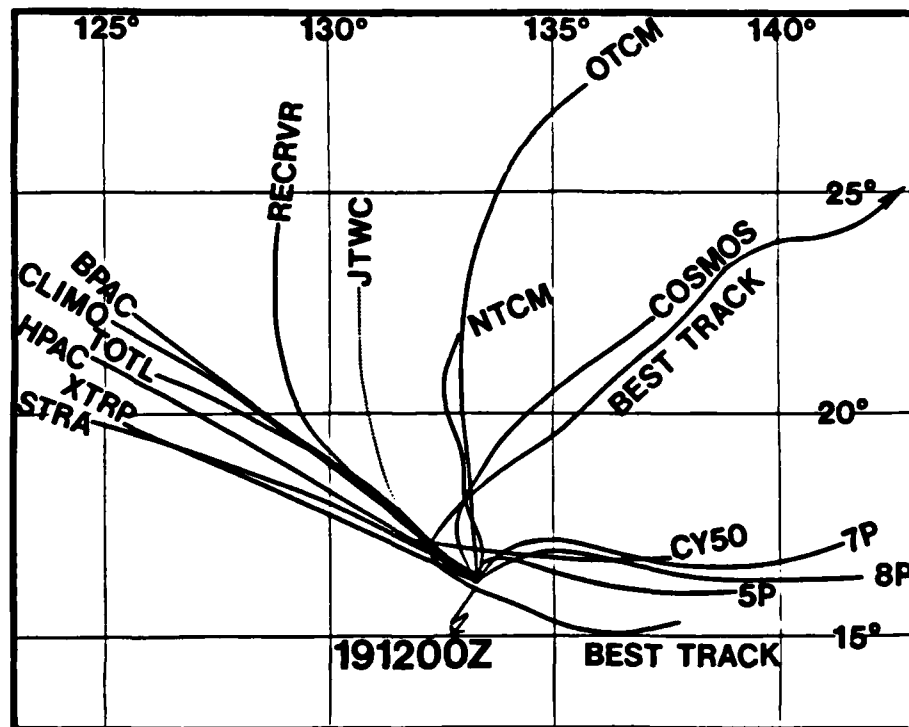


Fig. 2.1. The standard array of JTWC's objective forecasting techniques available to support the 19 August 1983 1200Z warning for Tropical Storm Dom. Included are the forecast issued at 191200Z and the eventual best track. (From 1983 Annual Tropical Cyclone Report.)

accuracy in track prediction would likely be obtainable. A statistical-dynamical model such as the one developed and detailed in this paper permits such a man-machine interface.

In addition, the method with which the prognostic data, whether they be perfect-prog, MOS or SMOS, are introduced into the statistical scheme appears to be the key to limiting the amount of degradation all statistical-dynamical models suffer when they are used operationally with actual forecast fields. An innovative approach to incorporating the prognostic data, as well as persistence and climatology, for use in a statistical model has been developed here and the results indicate that the problem of operational degradation may have been, to a large extent, solved.

3. DEVELOPMENTAL DATA BASE AND METHODOLOGY

Multiple linear regression techniques were used to develop forecast equations for the prediction of the east-west (U) and north-south (V) components of tropical cyclone motion. Predictors used, as shown in Fig. 3.1, were past 12- and 24-hour motion, steering at the 500 mb and 200 mb levels and the current and 24-hour changes of 500 mb geopotential heights and sea level pressures relative to the cyclone position at each of the three forecast times of $T=0$, $T=24$ hours, $T=48$ hours. This key point will be amplified later.

The developmental data were obtained from all tropical cyclone (including tropical depressions) cases between 1946-1981. No cases were omitted because of intensity or geographical limitations. The year 1948 and every third year thereafter were selected to be used as an independent set for testing. Years instead of cases were selected for the independent set because it was felt that this would result in a more representative selection for all three categories relative to the ridge. Enough years were selected for the independent set to provide approximately one-third the number of cases as the dependent set. The best track positions for the Atlantic basin were obtained from the Best Track of The National Hurricane Center while those for the other basins were obtained from the Annual Typhoon/Tropical Cyclone Reports published by the Joint Typhoon Warning Center (JTWC) on Guam. The synoptic data were derived from grid point analyses archived at The National Center for Atmospheric Research (NCAR). These grid point data were

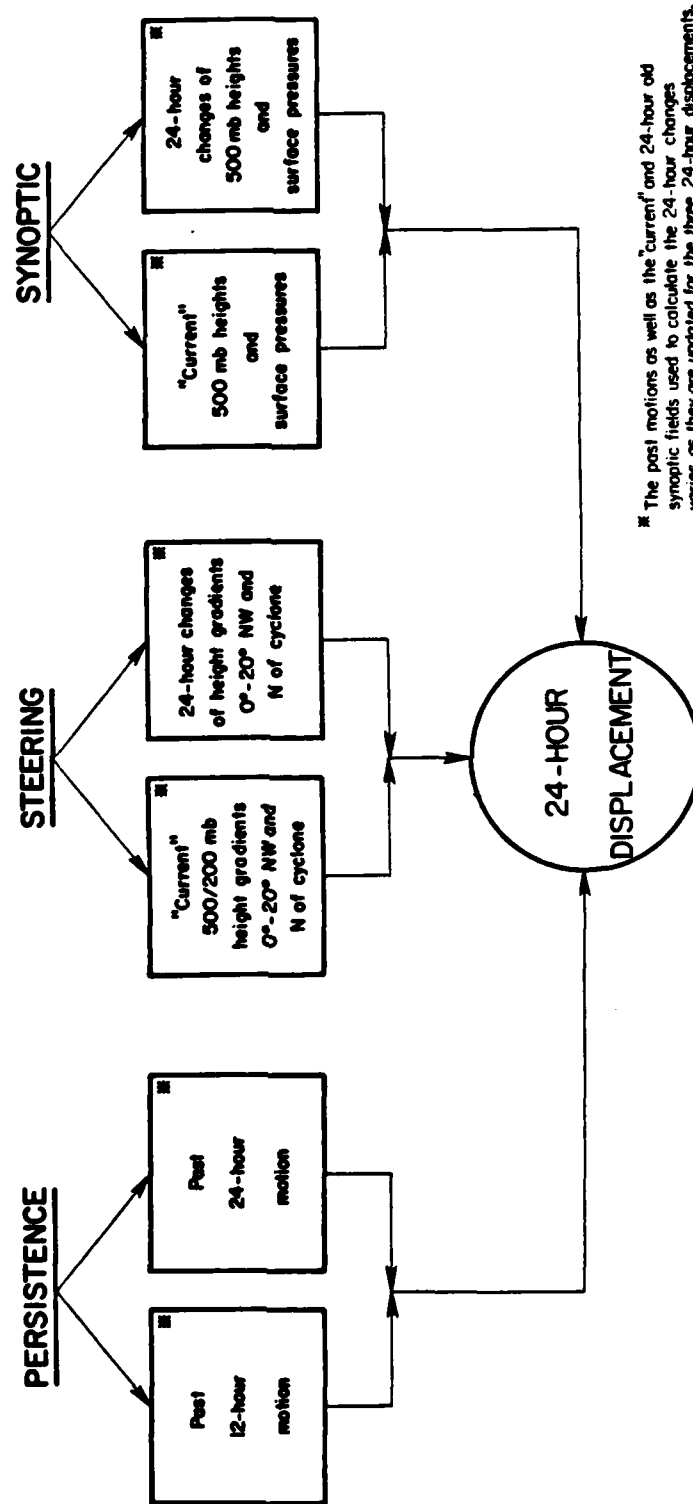


Fig. 3.1. The three components of predictors used by CSU84.

interpolated onto a $5^\circ \times 5^\circ$ grid (Fig. 3.2) with a domain of -10° to $+35^\circ$ latitude and $\pm 40^\circ$ longitude relative to the cyclone center to represent the synoptic forcing. The grid was offset poleward of the cyclone center to limit the number of grid points in the tropics, where the analyses tend to revert to climatology. A similar grid has been previously used by Xu and Gray (1982).

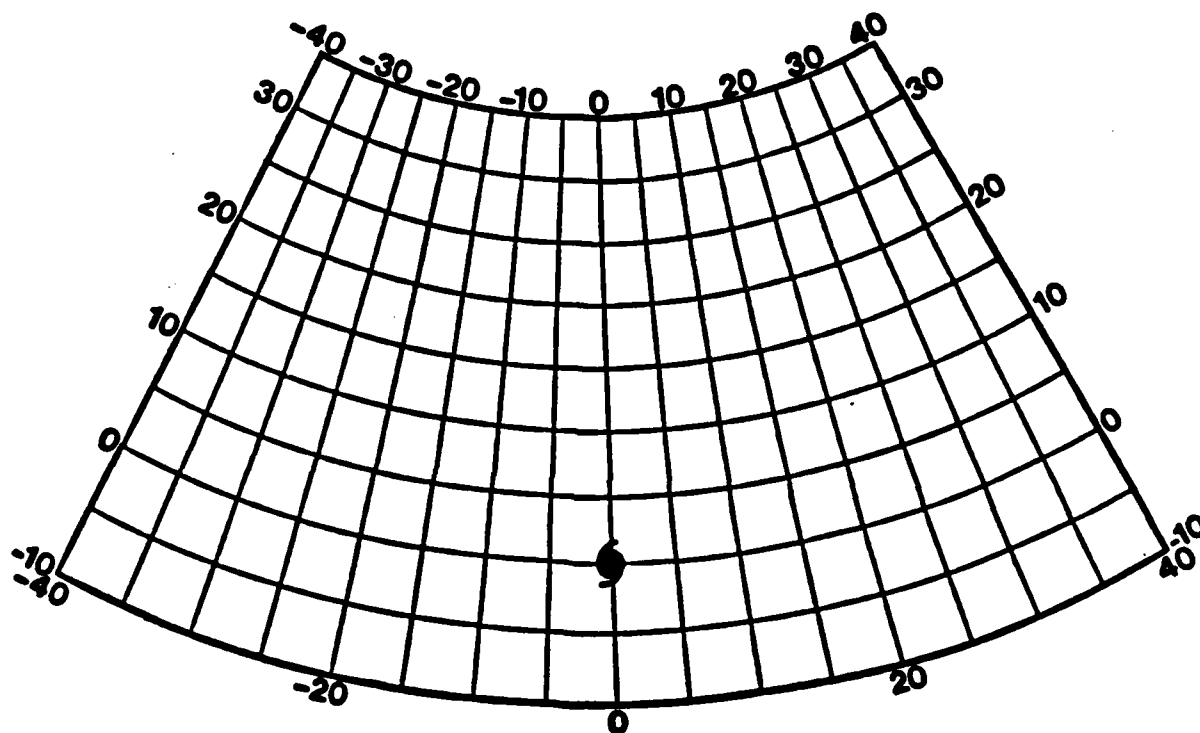


Fig. 3.2. $5^\circ \times 5^\circ$ geographical grid with a domain of -10 to $+35^\circ$ latitude and $\pm 40^\circ$ longitude relative to the cyclone center.

Actual prognostic fields of 500 mb D values and sea level pressures used to verify the model in a simulated operational setting were received from the Fleet Numerical Oceanography Center (FNOC), Monterey, CA, archived on a 63×63 hemispheric grid for the period 1968-1981. The 200 mb prognostic heights were not available from the Navy. Thus, testing of the model using actual progs was limited to a version of the model that did not include 200 mb steering predictors. The lack of 200

mb steering predictors did not present a problem for the NW Pacific since testing of the two versions revealed no significant differences in that ocean basin. However, differences in the Atlantic were sizeable and will be discussed in Chapter 5.

3.1 Stratification Scheme

Thirty-six years of tropical cyclone tracks (1946-1981) were subjectively analyzed along with daily 500 mb synoptic charts to select the recurvature point for each cyclone. Based on the recurvature point, every 00Z and 12Z position along with its subsequent 24-hour track segment was placed in one of three categories relative to the 500 mb subtropical ridge.

The south-of-ridge category is comprised of all cyclones that never recurved and the track segment of those recurving cyclones up to 24 hours prior to the recurvature point. The north-of-ridge category is comprised of all cyclones that existed north of the ridge throughout their lifetime and the track segment of those recurving cyclones beyond 24 hours after the recurvature point. The on-the-ridge category is comprised of the track segment of recurving cyclones between 24 hours before and 24 hours after the recurvature point.

Because of the frequent observation of recurving cyclones in the NW Pacific that exhibit long northward tracks before turning eastward, the criteria for stratifying the cyclone tracks relative to the ridge were modified for the NW Pacific and North Indian Oceans. Instead, the south-of-ridge category includes those recurving cyclones up to the point where their direction of motion (DOM) became greater than 330° . The north-of-ridge category includes those recurving cyclones beyond the point where their DOM became greater than 30° . The on-the-ridge

category is comprised of the track segment of recurving cyclones where the DCM is between 330° and 30° .

In an attempt to better forecast the extreme cases (which statistical methods frequently fail to do), the three categories were further separated into fast and slow motion groups based on the long wave pattern as depicted by the 500 mb height difference at certain longitudes along a chosen latitude. The specific grid points at which the height differences were noted were determined from the composition of fast minus slow cyclones performed by Xu and Gray (1982) as shown in Figs. 3.3 and 3.4 for the Atlantic and NW Pacific. Based on their composition, a quantity to be used for categorizing the speed for the Atlantic cyclones was calculated according to:

$$H_{15,-40} + H_{15,25} - 2 \times H_{15,-5} \quad \text{for cyclones north of the ridge}$$

$$H_{10,10} - H_{10,-15} - 20 \quad \text{for cyclones on the ridge}$$

$$2 \times H_{20,5} - H_{20,-25} - H_{20,25} \quad \text{for cyclones south of the ridge}$$

and for the Pacific:

$$H_{10,-35} + H_{10,15} - 2 \times H_{10,-5} \quad \text{for cyclones north of the ridge}$$

$$H_{10,10} - H_{10,-5} \quad \text{for cyclones on the ridge}$$

$$2 \times H_{15,0} - H_{15,-30} - H_{15,40} \quad \text{for cyclones south of the ridge}$$

H is the 500 mb height in meters and the subscripts indicate the degrees of latitude and longitude away from the cyclone center where the heights are to be observed. Latitudes are positive poleward of the cyclone and longitudes are positive eastward of the cyclone center.

If the calculated quantity was greater than or equal to zero, the long wave pattern was assumed to be favorable for fast motion so the cyclone was placed in the fast category. If the quantity was less than

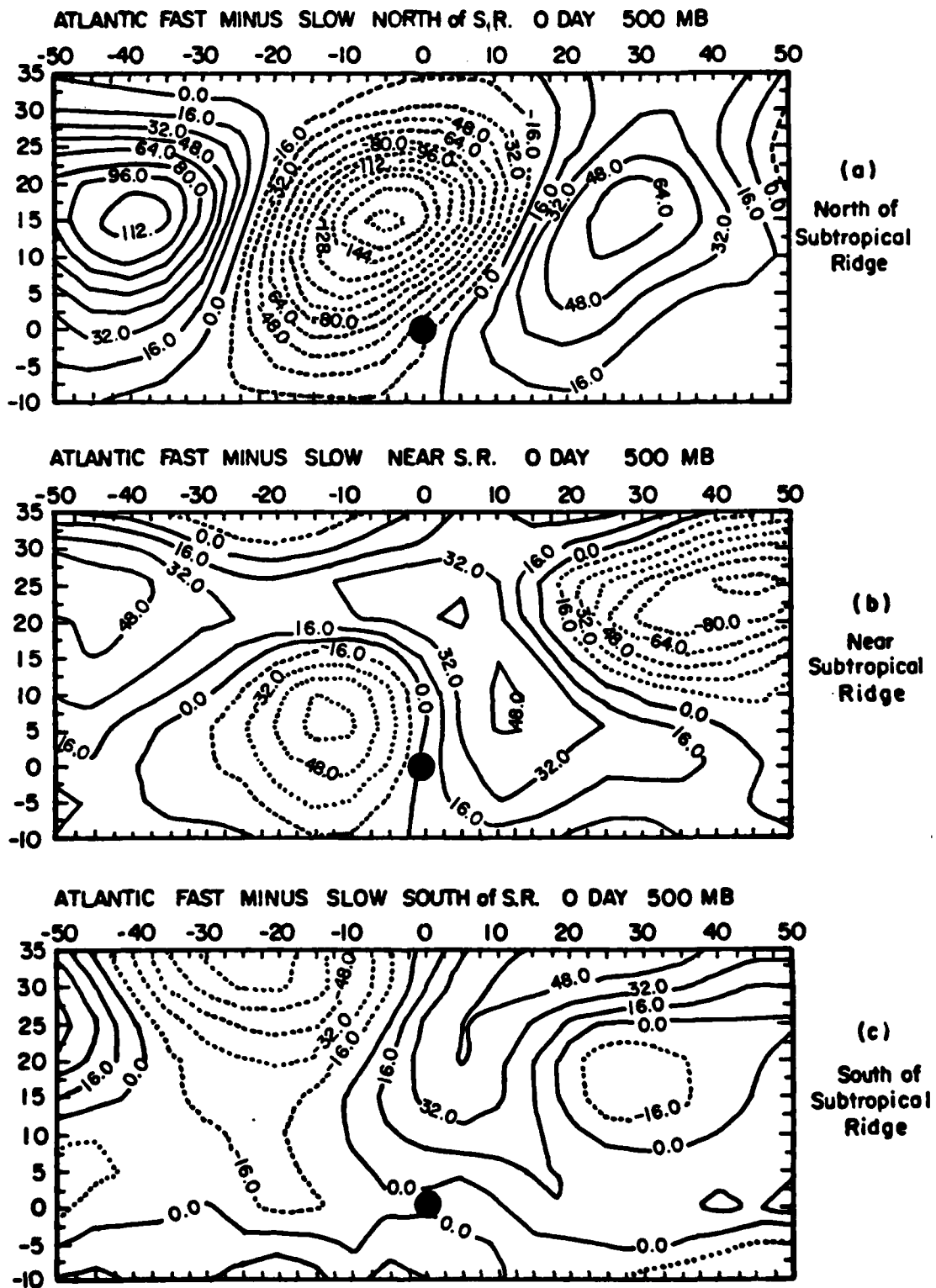


Fig. 3.3. 500 mb composite height differences in meters of fast minus slow cyclones in the Atlantic. The large dot marks the position of the cyclone. (From Xu and Gray, 1982).

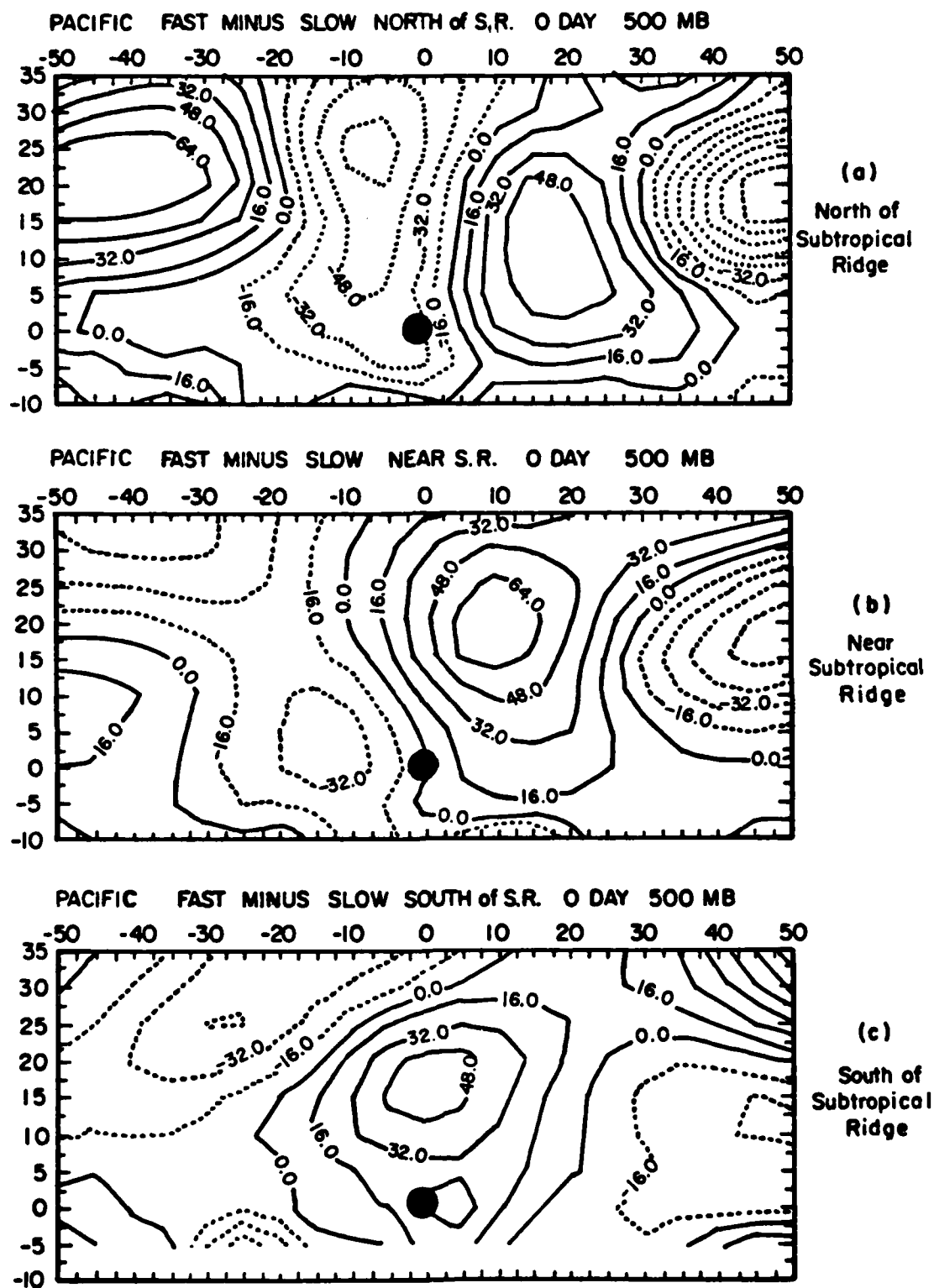


Fig. 3.4. 500 mb composite height differences in meters of fast minus slow cyclones in the Pacific. The large dot marks the position of the cyclone. (From Xu and Gray, 1982).

zero, the long wave pattern was assumed to be favorable for slow motion so the cyclone was placed in the slow category. It was hoped that this screening would be able to omit the slow moving cyclones (less than 2.5 m/s) from one set of equations and the fast moving cyclones (greater than 7.5 m/s) from the other set of equations.

In a conceptual sense, as shown in Figs. 3.5 through 3.7, different 500 mb long wave patterns are associated with fast and slow motion and it was felt that this procedure would result in a crude classification according to synoptic types in a manner similar to the scheme proposed by Tse (1966) for typhoon forecasting in the Pacific. If this theory holds, then certain predictors would be selected in different orders or given different weights for the fast and slow cases.

3.2 24-Hour Time Steps

For extended forecast periods, a likely weakness of a stratification based on the position of the cyclone relative to the ridge is that a tropical cyclone's position relative to the ridge may change over a span of three days. Thus, although the initial position of the cyclone may place it, for example, south of the ridge, it may be located north of the ridge 48 hours later and the environmental influences affecting its movement over the next 24 hours will certainly differ from those affecting its movement had it remained south of the ridge during the entire 72-hour period.

In order to eliminate the problem of a cyclone initially in one category moving into another category during the course of a 72-hour motion, and also to attempt to better describe the environment in which the cyclone was embedded as it changed over the period of 72 hours, the 72-hour period was segmented into three 24-hour periods. The segmenting

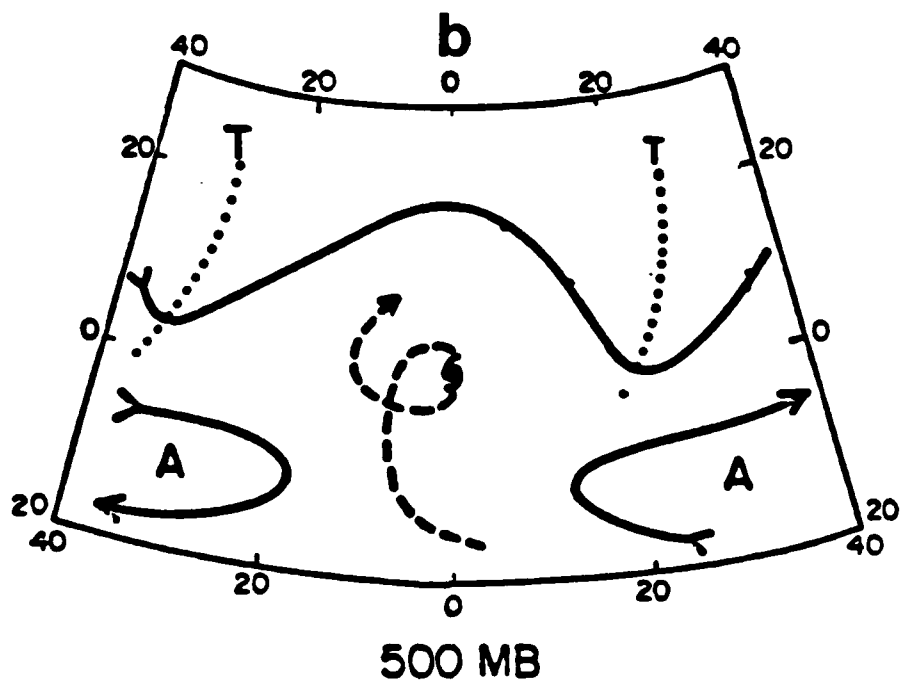
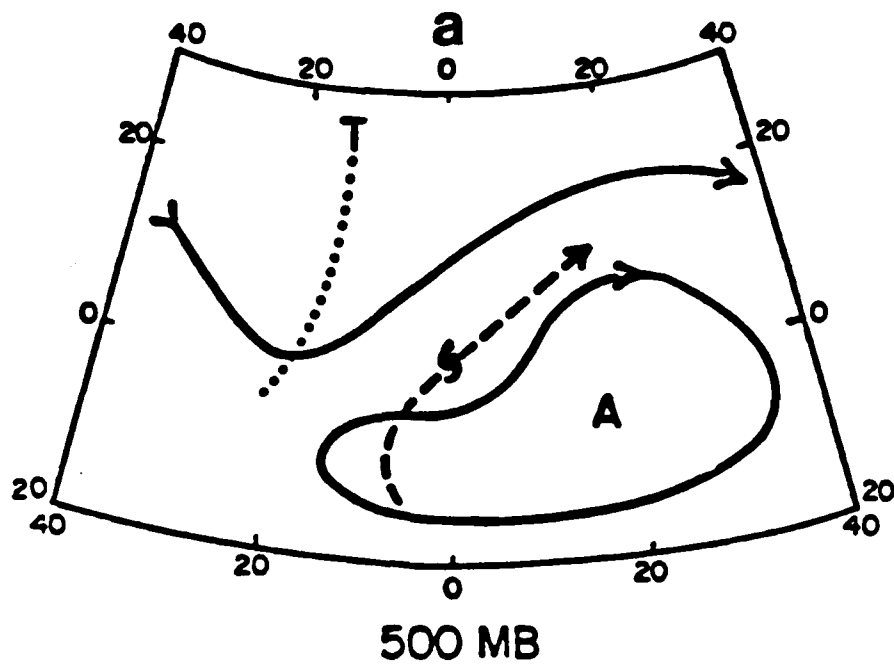


Fig. 3.5. a) Favorable height pattern for fast motion north of the subtropical ridge. b) Typical height pattern for slow motion north of the subtropical ridge. (From Xu and Gray, 1982.)

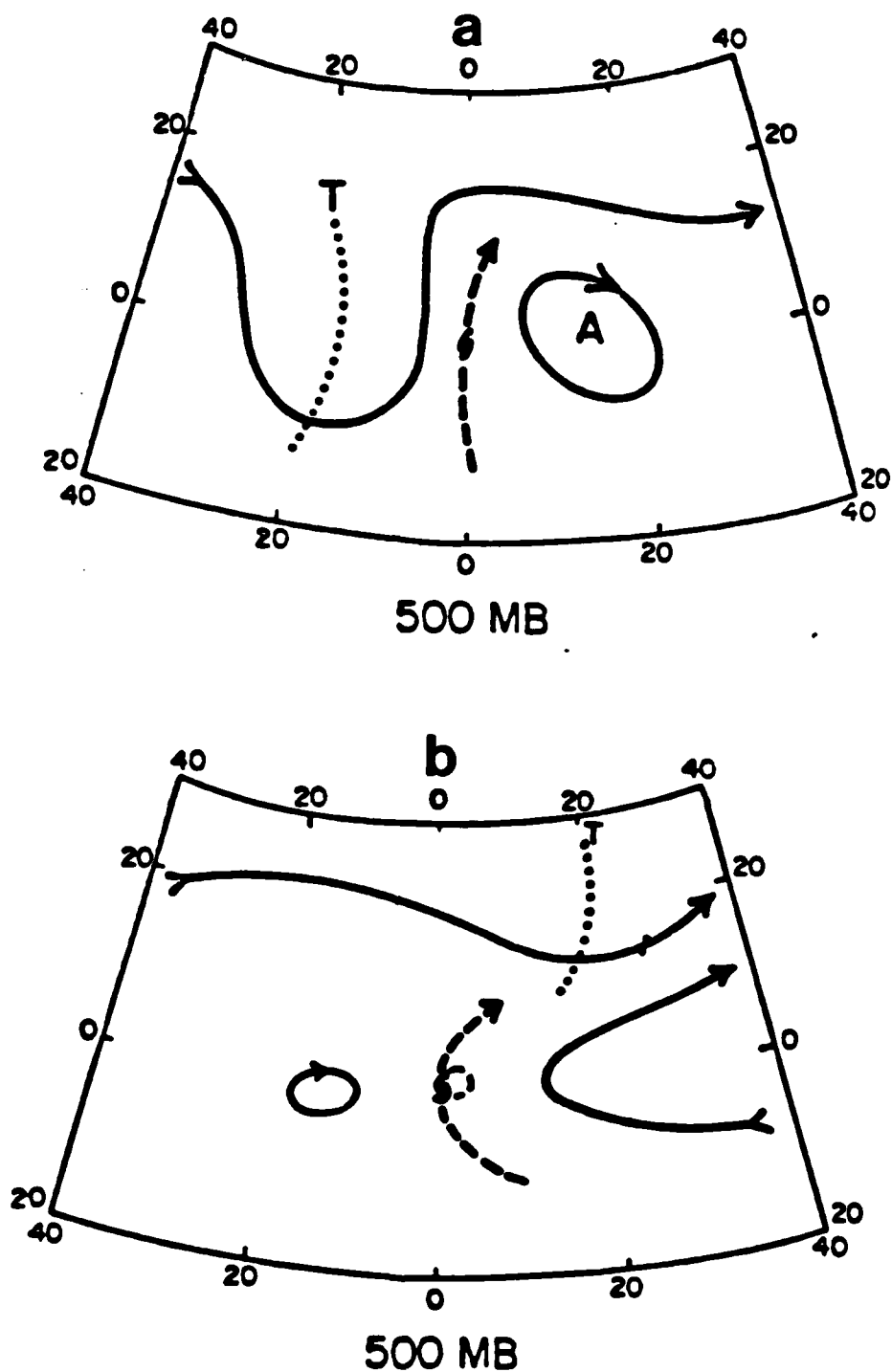


Fig. 3.6. a) Typical height pattern favorable for fast motion on the subtropical ridge. b) Typical height pattern for slow motion on the subtropical ridge. (From Xu and Gray, 1982.)

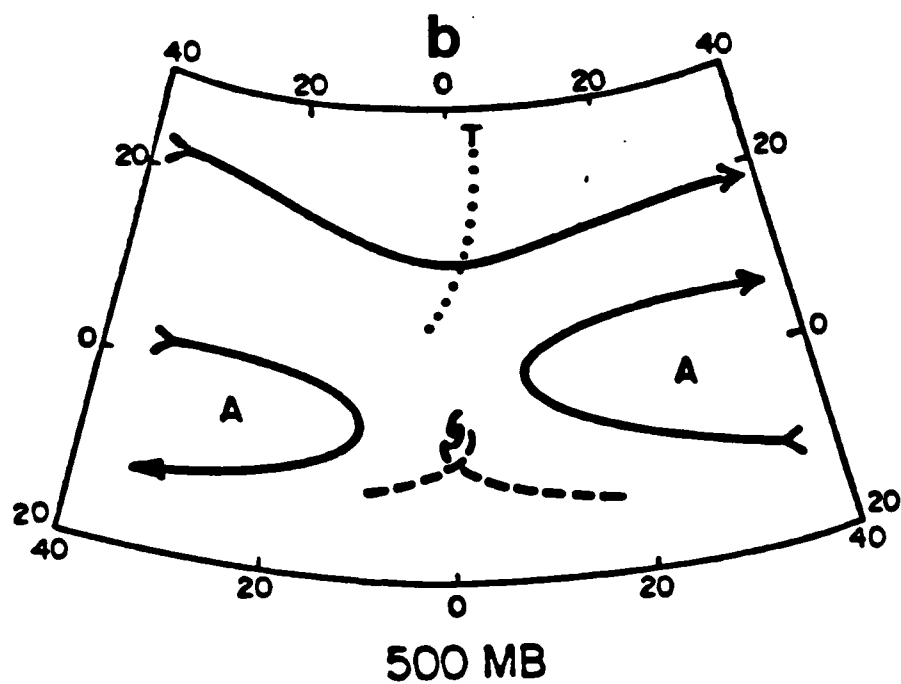
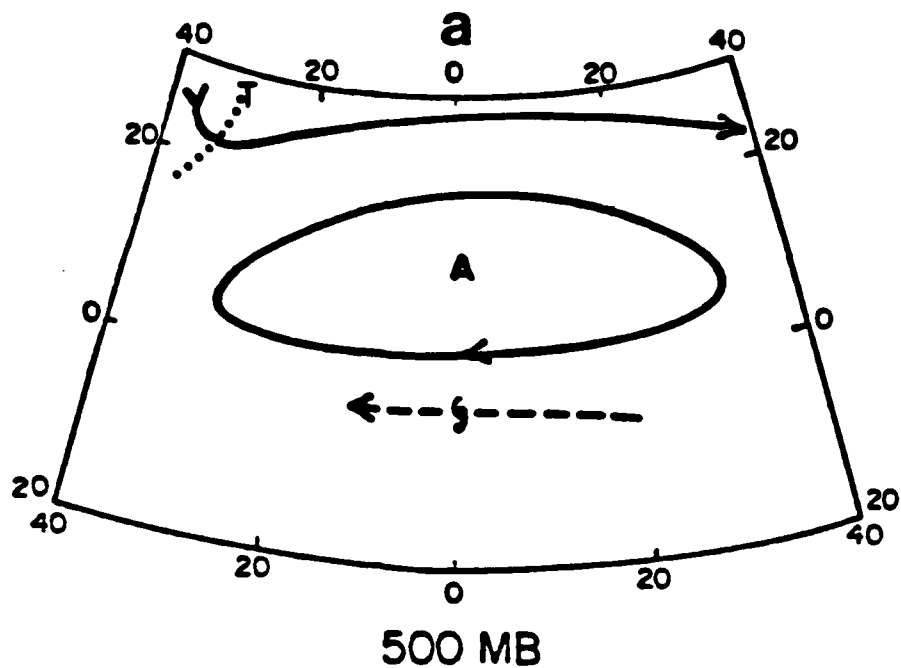


Fig. 3.7. a) Favorable height pattern for fast motion south of the subtropical ridge. b) Typical height pattern for slow motion south of the subtropical ridge. (From Xu and Gray, 1982.)

of 72-hour motion into 3 discrete 24-hourly time steps departs from the traditional statistical approach. There is an important distinction between CSU84 and the other statistical models in forming the developmental set. The other models require 72-hour tracks for each sample case whereas each sample case for CSU84 is composed of 24-hour tracks. Thus, it is possible to get many more cases to develop the regression equations for the CSU84 model. For the Atlantic, there are 977 cases for the south-of-ridge category, 1034 cases for the north-of-ridge category and 371 cases for the on-the-ridge category. For the NW Pacific, there are 4074 cases south of the ridge, 799 cases north of the ridge and 973 cases on the ridge. With the discretized steps, CSU84 calculates new past-motion persistence predictors and updates synoptic grid-point data relative to the new cyclone position at the start of each 24-hour forecast. The direction of motion over the previous 24 hours or a subjective analysis of the new position of the cyclone relative to the subtropical ridge is used to determine changeover from one stratification class to another. With the objective method of changing categories for cyclones in the south-of-ridge category, if the motion over the previous 24-hour period indicates a heading between 330° and 30° , that segment is placed in the on-the-ridge category for the formulation of the next 24-hour motion. Similarly, for cyclones in the south-of-ridge or on-the-ridge categories, if the motion over the previous 24-hour period is between 31° and 120° , that segment is placed in the north-of-ridge category for the formulation of the next 24-hour motion. The perfect-prog approach is taken to provide the new synoptic information. In an operational environment, the 24- and 48-hour 500 mb height and surface pressure prognostic fields would be used to provide

the information to formulate the 48-hour and 72-hour forecast motions, respectively. In other words, the 24-hour prognostic fields are applied to compute only the 24 to 48 hour motion and the 48-hour prognostic fields are applied to compute only the 48 to 72 hour motion. This is a significant departure from the traditional method of introducing prognostic data. Figure 3.8 is a flowchart depicting the 3-step procedure for arriving at the 24-, 48- and 72-hour forecast positions.

3.3 Application of Prognostic Data

The method of applying the prognostic data in CSU84 is unique. Other statistical models that employ prognostic data invariably use several forecast fields (24-, 36-, and 48-hour) for every forecast period, i.e., 0 to 12, 0 to 24, 0 to 36, 0 to 48, 0 to 72. The weakness of such an approach is, as pointed out by Neumann (1975), the over-weighting of the predictors from the prognostic data fields at the expense of observed data fields. This is understandable when the perfect-prog approach is used to introduce the prognostic data since all the prog data would be "perfect" — the data come from verifying analysis fields. Thus, it is of no surprise that these models degrade tremendously when actual forecast fields, which are not as accurate as the perfect-prog development data, are used to introduce the synoptic predictors in operational use. This point will be amplified in Chapter 5.

The unique method of applying prognostic data developed in CSU84 minimizes this degradation in two ways. First, by using just the current and 24-hour old analyses to compute the first 24 hours of motion, one has a "solid" 24-hour forecast position on which to build a 48-hour forecast based on prognostic data to arrive at a 72-hour forecast position. Second, the 48-hour forecast position is computed

Flow Chart To Compute The 24-HR, 48-HR, And 72-HR Forecast Positions

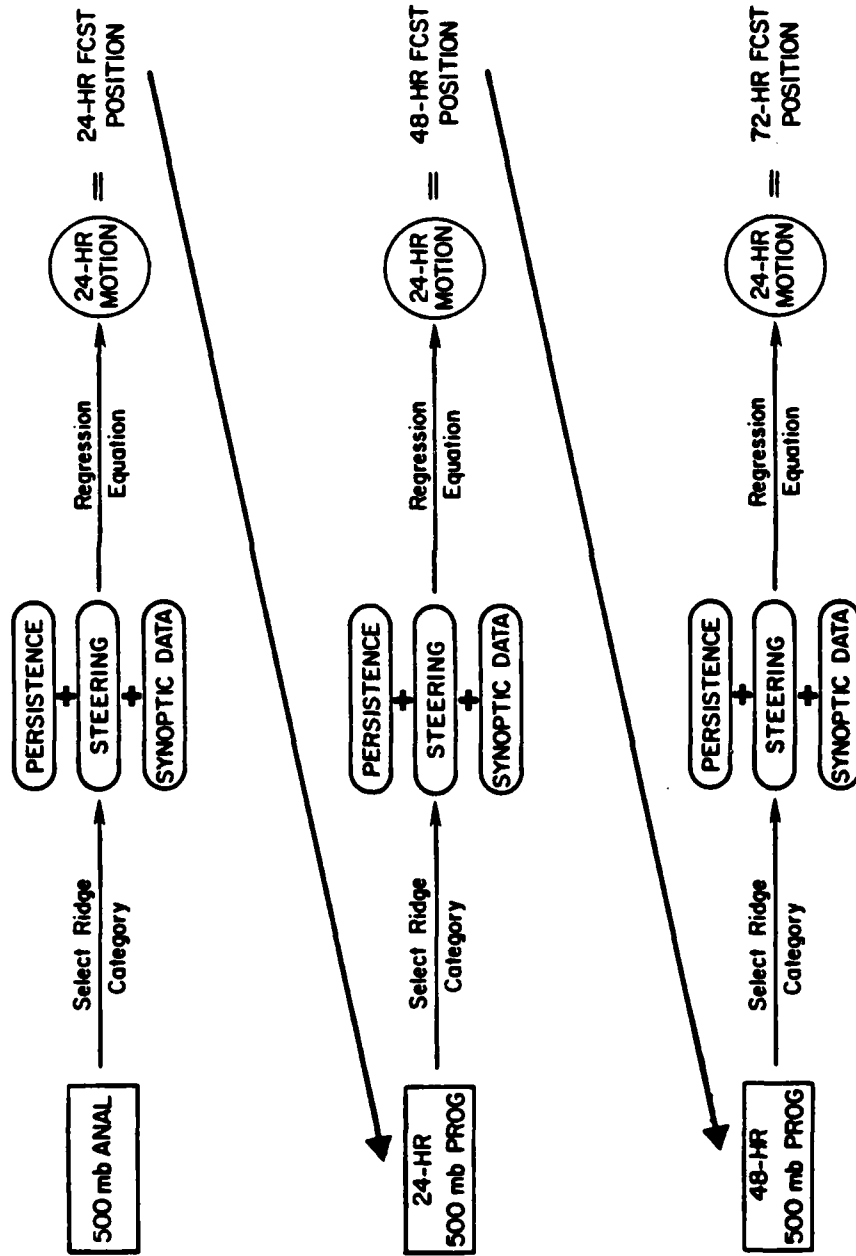


Fig. 3.8. 3-step flow chart depicting the procedure for computing the 24-, 48- and 72-hour forecast positions.

based on a 24-hour motion using the 24-hour forecast fields and the initial analysis fields to provide the tendencies of heights and pressures. Hence, just one forecast field is required to compute the second 24-hour motion. Thus, it is only the third and final 24-hour motion that depends on two forecast fields (24-hour and 48-hour). It would appear logical to shorten the forecast interval that a scheme relies on as much as possible so that if the prog field is in error, the error in the ensuing forecast position will be kept to a minimum. Further, although one or both of the forecast fields may be in error, the tendencies may still be fairly accurate. Thus, by discretizing the 72-hour cyclone motion into three shorter 24-hour segments, the reliance of the forecast scheme on "perfect" synoptic data to predict a 24-hour motion should not be as unrealistic as the reliance it would have if it was used to predict a 72-hour motion. If this notion holds, then the degradation in skill one can expect when using actual prognostic data should not be as drastic with this scheme.

This CSU84 method certainly appears to be superior to ones that attempt to compute a 24-hour forecast position based on analyses as well as prognostic data and then to recompute 48 and 72 hours of motion always from the initial position using three forecast fields (24-, 36-, and 48-hour), all of which could contain significant errors.

A schematic diagram of the three steps needed for a forecast projection of 72 hours is presented in Fig. 3.9. Note that what is meant by past motion and current and 24-hour old synoptic data changes as each 24-hour displacement is stepped forward. As a result, the actual values of the selected predictors will change as the forecast

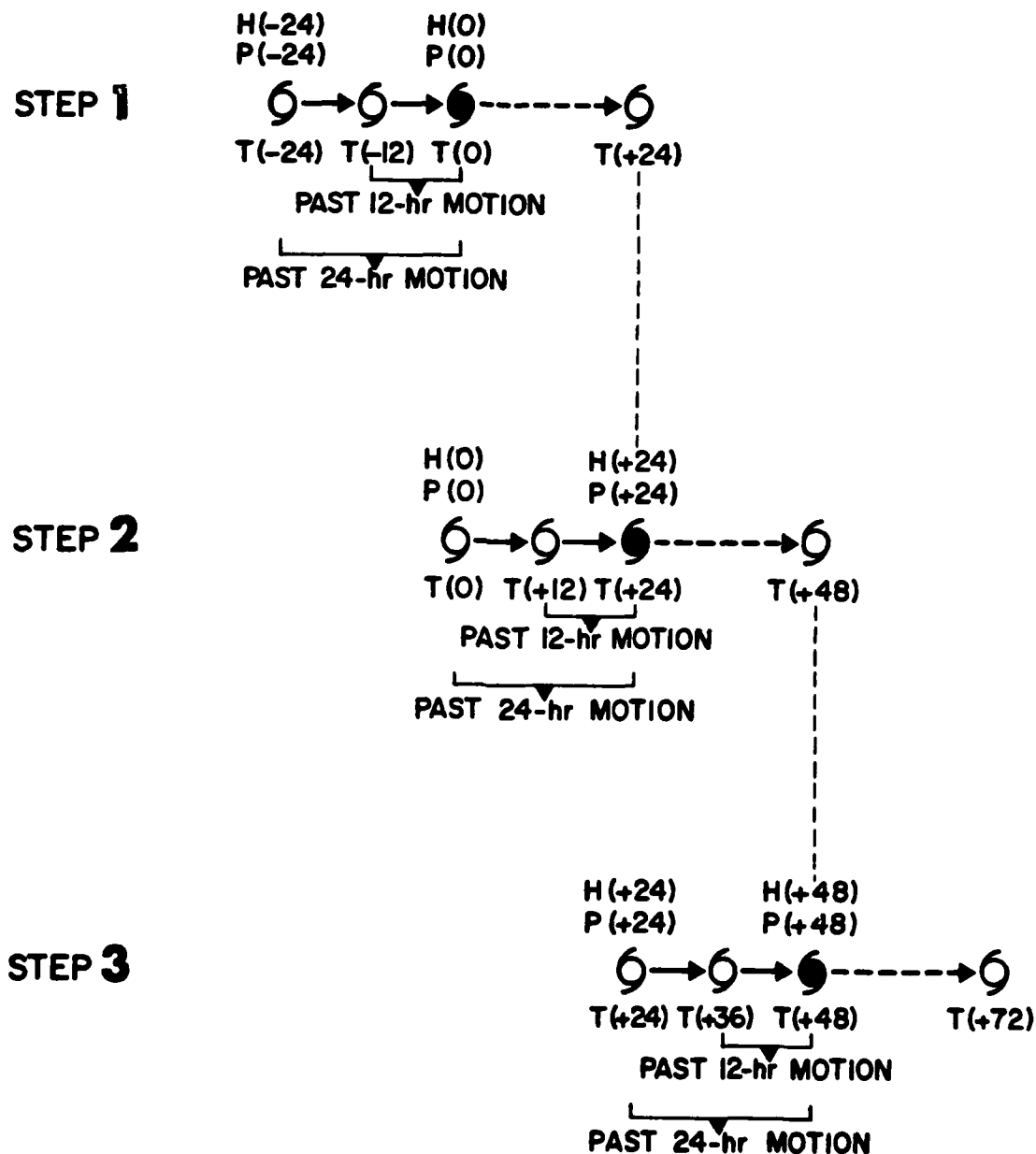


Fig. 3.9. Schematic diagram illustrating how the past motions and synoptic fields used to provide the predictors for a 24-hour displacement change relative to the new position of the cyclone.

positions are projected forward in time. This is because all of the predictors are relative to the position of the cyclone at the time they are applied. Hence, prognostic data are used as if they were analysis data at their respective valid times.

The cyclone symbols with the darkened circle are the positions at which the three 24-hour displacements are computed. The two cyclone symbols with the open circle to the left of these positions represent the 12- and 24-hour old positions relative to each of the three positions at which a 24-hour forecast is made. The cyclone symbol with the open circle to the right of the darkened circles is the 24-hour displacement. As the 72-hour forecast process is stepped forward in 24-hour increments, each 24-hour displacement position becomes the new position from which to compute the next 24-hour displacement.

The "H" and "P" above the cyclone symbols indicate which 500 mb height and surface pressure fields provide the required synoptic predictors to compute the displacements. With T_0 the time at the initial position, $H(0)$ and $P(0)$ corresponds to the current analyses, $H(-24)$ and $P(-24)$ correspond to 24-hour-old analyses, $H(+24)$ and $P(+24)$ correspond to the 24-hour prognoses and $H(+48)$ and $P(+48)$ correspond to the 48-hour prognoses. It must be kept in mind that the gridpoint predictors are relative to the position of the cyclone at the time each forecast is made, not relative to the initial position of the cyclone.

4. THE REGRESSION EQUATIONS

4.1 The Regression Equation

To develop the prediction equations, a stagewise-stepwise multiple linear regression procedure proposed by Lund (1971) was adopted. Due to the large number of both sample cases and potential predictors, the normal stepwise regression approach would have been inappropriate since just the two covariance arrays containing the sums of squares and cross-products would have exceeded the memory size of the largest available computers. With the procedure suggested by Lund, there is just one relative coefficient matrix instead of two covariance matrices.

The regression equations were obtained using various computational subroutines available in The International Mathematics and Statistics Libraries (IMSL, 1982) that reside on the NCAR CRAY-1 computer. The method employed was as follows:

- (1) Means, standard deviations and correlation coefficients were computed for each predictor
- (2) IMSL subroutine BECOVM computed the corrected sum of squares and cross-products
- (3) IMSL subroutine RLMUL performed an analysis of variance including the standard deviation of the residuals and the regression coefficient and intercept estimates.
- (4) IMSL subroutine RLRES performed a residual analysis on the predictors used in fitting a regression model. The residual from this

fitted model was used as the new dependent variable (predictand) and steps (1) - (4) repeated 20 times to select the 20 best predictors.

(5) IMSL subroutine RLSEP performed a forward stepwise regression analysis using the 20 predictors selected from the stagewise procedure to compute the regression coefficients. The process that is accomplished by the first four steps has also been referred to as successive elimination. After the removal of each selected predictor, a new residual is calculated with the remaining predictors and that becomes the new predictand with which the remaining predictors are correlated.

4.2 Geographical Inhomogeneity

Northern Hemisphere cyclone tracks exhibit significant regional variations. In the NW Pacific, the near-equatorial monsoon trough is responsible for easterly or erratic motion with low latitude cyclones. When cyclones manage to break through the subtropical ridge, they sometimes travel far poleward before being steered eastward by the westerlies. For the South China Sea region, complicated and conflicting wind flow patterns between the southwest monsoon flow and the continental northeasterlies lead to a strong vertical wind shear and extremely erratic motion is common. In the North Indian Ocean, weak steering currents lead to slow motion. In the Atlantic, cyclones generally track in a west to northwestward direction recurving at higher latitudes. The ratio of very fast and very slow moving cyclones to the total is high, however, resulting in difficult forecast situations.

Regression equations were therefore developed separately for the four geographical regions using the previous set of potential predictors but with slight regional changes. Due to the low annual frequency of

cyclones in the North Indian Ocean, it was necessary to use 500 mb computed geostrophic winds in place of 200 mb computed geostrophic winds since 200 mb data are available only after 1962. This permitted the use of the entire historical best tracks going back to 1946. In addition, to further increase the sample size, no speed stratification was attempted in the North Indian Ocean.

For the South China Sea, since the vertical shear of the steering flow appeared to be of overriding importance rather than the location of the mid-level subtropical ridge for cyclone motion in this region, these cyclones were not stratified relative to the 500 mb subtropical ridge. Storms in this region were also not stratified by speed both because they tend to move slowly and also in order to obtain as large a sample size as possible. Instead, additional steering levels - 700 mb and 850 mb - were incorporated in an attempt to better depict the steering flow at different vertical levels.

For the NW Pacific, two observed phenomena presented special difficulties in stratification. One was the erratic motion of cyclones embedded in the near-equatorial monsoon trough. The other was the long northward track of cyclones breaking through the subtropical ridge prior to being steered eastward by the upper level westerlies.

In the former case of anomalous motion, it is obvious that the direction of motion is a poor indicator of future motion. Instead of deleting these monsoon-trough cases, these cyclones were left intact in the developmental data set with the understanding that correlation of motion south of the ridge with synoptic predictors would not be as high as those for the Atlantic cyclones. To handle the long northward trek of cyclones in the Pacific, the criteria for the on-the-ridge category

was broadened to include all segments that had a direction of motion between 330° and 30° rather than restricting this category to 24 hours before and after the recurvature point.

4.3 The Potential Predictors

Equations for the east-west and north-south components of cyclone motion were developed by screening over 700 potential predictors. The potential predictors included the past 12-hour and past 24-hour east-west and north-south motions and grid point synoptic data of "current" and the past 24-hour changes of 500 mb heights and sea level pressures. Recall that all of the predictors are applied relative to a new cyclone position each time a 24-hour motion is computed. Thus, the synoptic grid and the 12- and 24-hour old cyclone positions needed to calculate the past motions move with the cyclone.

As a result, the analysis field valid at the initial time T_0 is the "current" synoptic field and that field, along with the analysis field valid at T_0 minus 24 hours (T_{-24}), are used to calculate the 24-hour changes of 500 mb heights and sea level pressures. These two fields are also used to compute the "current" and 24-hour changes of the steering predictors. Once the first 24-hour displacement has been stepped forward, the 24-hour forecast field valid at T_0 plus 24 hours (T_{+24}) becomes the "current" synoptic field and the analysis field at T_0 becomes the 24-hour-old field and all of the grid-point predictors as well as the updated persistence predictors are computed relative to the new cyclone position at T_{+24} . When the second 24-hour displacement is stepped forward from the T_{+24} cyclone position, the 48-hour forecast field valid at T_0 plus 48 hours (T_{+48}) becomes the "current" synoptic field and the forecast field valid at T_{+24} becomes the 24-hour-old

field. Then, all of the grid-point predictors as well as the updated persistence predictors are computed relative to the new cyclone position at T_{+48} . Using these updated predictors, the final 24-hour displacement is stepped forward from the T_{+48} cyclone position to determine the 72-hour forecast position. All references to steering winds apply to geostrophic winds which were calculated from the gradients of geopotential heights using the following formula:

For the wind at the cyclone center, the U and V components are computed as:

$$U = ((H_{-10,-10} + H_{-10,-5} + H_{-10,0} + H_{-10,5} + H_{-10,10}) - (H_{10,-10} + H_{10,-5} + H_{10,0} + H_{10,5} + H_{10,10})) / (5 \times \sin \phi)$$

$$V = ((H_{-10,10} + H_{-5,10} + H_{0,10} + H_{5,10} + H_{10,10}) - (H_{-10,-10} + H_{-5,-10} + H_{0,-10} + H_{5,-10} + H_{10,-10})) / (5 \times \sin (\phi) \times \cos (\phi))$$

For the wind 10° northwest of the cyclone center, the U and V components are computed as:

$$U = (H_{5,-10} - H_{15,-10}) / \sin (\phi)$$

$$V = (H_{10,-5} - H_{10,-15}) / (\sin (\phi) \times \cos (\phi))$$

For the wind 5° northwest of the cyclone center, the U and V components are computed as:

$$U = (H_{0,-5} - H_{10,-5}) / \sin (\phi)$$

$$V = (H_{5,0} - H_{5,-10}) / (\sin (\phi) \times \cos (\phi))$$

For the wind 10° north of the cyclone center, the U and V components are computed as:

$$U = (H_{5,0} - H_{15,0}) / \sin \phi$$

$$V = (H_{10,5} - H_{10,-5}) / (\sin \phi \times \cos \phi)$$

For the wind 5° north of the cyclone center, the U and V components are computed as:

$$U = (H_{0,0} - H_{10,0}) / \sin \phi$$

$$V = (H_{5,5} - H_{5,-5}) / (\sin \phi \times \cos \phi)$$

For the wind 15° northwest of the cyclone center, the U and V components are computed as:

$$U = (H_{10,-15} - H_{20,-15}) / \sin \phi$$

$$V = (H_{15,-10} - H_{15,-20}) / (\sin \phi \times \cos \phi)$$

For the wind 20° northwest of the cyclone center, the U and V components are computed as:

$$U = (H_{15,-20} - H_{25,-20}) / \sin \phi$$

$$V = (H_{20,-15} - H_{20,-25}) / (\sin \phi \times \cos \phi)$$

For the wind 15° north of the cyclone center, the U and V components are computed as:

$$U = (H_{10,0} - H_{20,0}) / \sin \phi$$

$$V = (H_{15,5} - H_{15,-5}) / (\sin \phi \times \cos \phi)$$

For the wind 20° north of the cyclone center, the U and V components are computed as:

$$U = (H_{15,0} - H_{25,0}) / \sin \phi$$

$$V = (H_{20,5} - H_{20,-5}) / (\sin \phi \times \cos \phi)$$

$H_{i,j}$ is the 500 mb or 200 mb height at grid point i,j where i represents latitude and j represents longitude from the cyclone center. Latitudes are positive to the north and longitudes are positive to the east of the cyclone center. ϕ is the latitude of the grid point at which the steering wind is being computed.

Table 4.1 lists the 732 potential predictors for the Atlantic and NW Pacific. Table 4.2 lists the 728 potential predictors for the North Indian Ocean and Table 4.3 lists the 1364 potential predictors for the South China Sea. The list of 728 potential predictors for the Atlantic and NW Pacific using 500 mb steering instead of 200 mb steering is identical to those listed for the North Indian Ocean. The 500 mb steering wind over the cyclone center is computed for all versions of the model. This is the reason for the difference in the number of predictors between the two versions for the NW Pacific and the Atlantic.

Variations of the model using surface pressure gradients as well as thickness of the surface to 500 mb surfaces were tested. However, the screening program failed to select either category of predictors.

The three categories of predictors used in the CSU84 prediction model were shown in Chapter 3. As explained earlier, the "current" and the 24-hour-old synoptic data are not always the analysis and the 24-hour-old analysis at the initial time for the 24- to 48- and 48- to 72-hour predictions. These fields change as the three 24-hour displacements are stepped forward. In development, a perfect-prog approach was used to introduce analysis data valid at the verifying times. In actual practice, 24- and 48-hour forecast fields would be used at their verifying times.

Importance of Different Predictors. The reduction of variance due to each of the three categories of predictors was examined for Atlantic and Pacific. A few surprising observations are evident from Table 4.4. One was the significant difference in the variance reducing potential of the steering component for the north-of-ridge and on-the-ridge between the Atlantic and NW Pacific.

TABLE 4.1

The 732 potential forecast predictors for the Atlantic and NW Pacific

1-170	24-hr 500 mb height changes at the 17 X 10 grid points [ΔH]
171-340	500 mb heights at the 17 X 10 grid points [H]
341-510	24-hr sea level pressure changes at the 17 X 10 grid points (mb) [ΔP]
511-680	Sea level pressures at the 17 X 10 grid points (mb) [P]
681-682	Past 24-hr U and V cyclone motion (km/hr) [U_{-24} , V_{-24}]
683-684	Past 12-hr U and V cyclone motion (km/hr) [U_{-12} , V_{-12}]
685-686	500 mb U and V wind components at cyclone center [Φ_{500u} , Φ_{500v}]
687-688	24-hr 500 mb U and V wind change at cyclone center [$\Delta\Phi_{500u}$, $\Delta\Phi_{500v}$]
689-690	200 mb U and V wind components at cyclone center [Φ_{200u} , Φ_{200v}]
691-692	24-hr 200 mb U and V wind change at cyclone center [$\Delta\Phi_{200u}$, $\Delta\Phi_{200v}$]
693-694	200 mb U and V wind components 10° northwest of cyclone center [$\Phi_{200NW10u}$, $\Phi_{200NW10v}$]
695-696	24-hr 200 mb U and V wind change 10° northwest of cyclone center [$\Delta\Phi_{200NW10u}$, $\Delta\Phi_{200NW10v}$]
697-698	200 mb U and V wind components 5° northwest of cyclone center [$\Phi_{200NW5u}$, $\Phi_{200NW5v}$]
699-700	24-hr 200 mb U and V wind change 5° northwest of cyclone center [$\Delta\Phi_{200NW5u}$, $\Delta\Phi_{200NW5v}$]
701-702	200 mb U and V wind difference between 10° northwest and 5° northwest of cyclone center [$\Phi_{200NW10-5u}$, $\Phi_{200NW10-5v}$]
703-704	24-hr 200 mb U and V wind change difference between 10° northwest and 5° northwest of cyclone center [$\Delta\Phi_{200NW10-5u}$, $\Delta\Phi_{200NW10-5v}$]
705-706	200 mb U and V wind components 10° north of cyclone center [$\Phi_{200N10u}$, $\Phi_{200N10v}$]
707-708	24-hr 200 mb U and V wind change 10° north of cyclone center [$\Delta\Phi_{200N10u}$, $\Delta\Phi_{200N10v}$]

TABLE 4.1 (cont'd)

709-710	200 mb U and V wind components 5° north of cyclone center [Φ_{200N5u} , Φ_{200N5v}]
711-712	24-hr 200 mb U and V wind change 5° north of cyclone center [$\Delta\Phi_{200N5u}$, $\Delta\Phi_{200N5v}$]
713-714	200 mb U and V wind difference between 10° north and 5° north of cyclone center [$\Phi_{200N10-5u}$, $\Phi_{200N10-5v}$]
715-716	24-hr 200 mb U and V wind change difference between 10° north and 5° north of cyclone center [$\Delta\Phi_{200N10-5u}$, $\Delta\Phi_{200N10-5v}$]
717-718	200 mb U and V wind components 15° northwest of cyclone center [$\Phi_{200NW15u}$, $\Phi_{200NW15v}$]
719-720	24-hr 200 mb U and V wind change 15° northwest of cyclone centers [$\Delta\Phi_{200NW15u}$, $\Delta\Phi_{200NW15v}$]
721-722	200 mb U and V wind components 20° northwest of cyclone centers [$\Phi_{200NW20u}$, $\Phi_{200NW20v}$]
723-724	24-hr 200 mb U and V wind change 20° northwest of cyclone center [$\Delta\Phi_{200NW20u}$, $\Delta\Phi_{200NW20v}$]
725-726	200 mb U and V wind components 15° north of cyclone center [$\Phi_{200N15u}$, $\Phi_{200N15v}$]
727-728	24-hr 200 mb U and V wind change 15° north of cyclone center [$\Delta\Phi_{200N15u}$, $\Delta\Phi_{200N15v}$]
729-730	200 mb U and V wind components 20° north of cyclone center [$\Phi_{200N20u}$, $\Phi_{200N20v}$]
731-732	24-hr 200 mb U and V wind change 20° north of cyclone center [$\Delta\Phi_{200N20u}$, $\Delta\Phi_{200N20v}$]

TABLE 4.2

The 728 Potential Forecast Predictors For The North Indian Ocean

1-170	24-hr 500 mb height change at the (17 X 10) grid points [AH]
171-340	500 mb heights at the 17 X 10 grid points [H]
341-510	24-hr sea level pressure change at the 17 X 10 grid points (mb) [AP]
511-680	Sea level pressures at the 17 X 10 grid points (mb) [P]
681-682	Past 24-hr U and V cyclone motion (km/hr) [U_{-24} , V_{-24}]
683-684	Past 12-hr U and V cyclone motion (km/hr) [U_{-12} , V_{-12}]
685-686	500 mb U and V wind components at cyclone center [Φ_{500u} , Φ_{500v}]
687-688	24-hr 500 mb U and V wind change at cyclone center [$\Delta\Phi_{500u}$, $\Delta\Phi_{500v}$]
689-690	500 mb U and V wind components 10° northwest of cyclone center [$\Phi_{500NW10u}$, $\Phi_{500NW10v}$]
691-692	24-hr 500 mb U and V wind change 10° northwest of cyclone center [$\Delta\Phi_{500NW10u}$, $\Delta\Phi_{500NW10v}$]
693-694	500 mb U and V wind components 5° northwest of cyclone center [$\Phi_{500NW5u}$, $\Phi_{500NW5v}$]
695-696	24-hr 500 mb U and V wind change 5° northwest of cyclone center [$\Delta\Phi_{500NW5u}$, $\Delta\Phi_{500NW5v}$]
697-698	500 mb U and V wind difference between 10° northwest and 5° northwest of cyclone center [$\Phi_{500NW10-5u}$, $\Phi_{500NW10-5v}$]
699-700	24-hr 500 mb U and V wind change difference between 10° northwest and 5° northwest of cyclone center [$\Delta\Phi_{500NW10-5u}$, $\Delta\Phi_{500NW10-5v}$]
701-702	500 mb U and V wind components 10° north of cyclone center [$\Phi_{500N10u}$, $\Phi_{500N10v}$]
703-704	24-hr 500 mb U and V wind change 10° north of cyclone center [$\Delta\Phi_{500N10u}$, $\Delta\Phi_{500N10v}$]
705-706	500 mb U and V wind components 5° north of cyclone center [Φ_{500N5u} , Φ_{500N5v}]

TABLE 4.2 (cont'd)

707-708	24-hr 500 mb U and V wind change 5° north of cyclone center [$\Delta\Phi_{500N5u}$, $\Delta\Phi_{500N5v}$]
709-710	500 mb U and V wind difference between 10° north and 5° north of cyclone center [$\Phi_{500N10-5u}$, $\Phi_{500N10-5v}$]
711-712	24-hr 500 mb U and V wind change difference between 10° north and 5° north of cyclone center [$\Delta\Phi_{500N10-5u}$, $\Delta\Phi_{500N10-5v}$]
713-714	500 mb U and V wind components 15° northwest of cyclone center [$\Phi_{500NW15u}$, $\Phi_{500NW15v}$]
715-716	24-hr 500 mb U and V wind change 15° northwest of cyclone center [$\Delta\Phi_{500NW15u}$, $\Delta\Phi_{500NW15v}$]
717-718	500 mb U and V wind components 20° northwest of cyclone center [$\Phi_{500NW20u}$, $\Phi_{500NW20v}$]
719-720	24-hr 500 mb U and V wind change 20° northwest of cyclone center [$\Delta\Phi_{500NW20u}$, $\Delta\Phi_{500NW20v}$]
721-722	500 mb U and V wind components 15° north of cyclone center [$\Phi_{500N15u}$, $\Phi_{500N15v}$]
723-724	24-hr 500 mb U and V wind change 15° north of cyclone center [$\Delta\Phi_{500N15u}$, $\Delta\Phi_{500N15v}$]
725-726	500 mb U and V wind components 20° north of cyclone center [$\Phi_{500N20u}$, $\Phi_{500N20v}$]
727-728	24-hr 500 mb U and V wind change 20° north of cyclone center [$\Delta\Phi_{500N20u}$, $\Delta\Phi_{500N20v}$]

TABLE 4.3

The Potential Forecast Predictors For The South China Sea

1-170	24-hr 500 mb height changes at the 17 X 10 grid points [ΔH]
171-340	500 mb heights at the 17 X 10 grid points [H]
341-510	24-hr sea level pressure changes at the 17 X 10 grid points (mb) [ΔP]
511-680	Sea level pressures at the 17 X 10 grid points (mb) [P]
681-850	24-hr 700 mb height changes at the 17 X 10 grid points [$\Delta H7$]
851-1020	700 mb heights at the 17 X 10 grid points [H7]
1021-1190	24-hr 850 mb height changes at the 17 X 10 grid points [$\Delta H8$]
1191-1360	850 mb heights at the 17 X 10 grid points [H8]
1361-1362	Past 24-hr U and V cyclone motion (km/hr) [U_{-24} , V_{-24}]
1363-1364	Past 12-hr U and V cyclone motion (km/hr) [U_{-12} , V_{-12}]

TABLE 4.4

Percent of variance reduction due to the three categories of predictors (see Fig. 3.7) for the Atlantic and the NW Pacific. Version CSU84₅₀₀ of the model uses 500 mb steering. Version CSU84₂₀₀ uses 200 mb steering.

<u>Atlantic</u>		<u>U</u>		<u>V</u>	
		CSU84 ₅₀₀	CSU84 ₂₀₀	CSU84 ₅₀₀	CSU84 ₂₀₀
<u>North</u>	Persistence	17	63	11	11
	Steering	0	4	52	53
	Synoptic	65	16	15	16
<u>On</u>	Persistence	9	8	10	10
	Steering	49	53	63	59
	Synoptic	26	21	14	12
<u>South</u>	Persistence	12	52	46	44
	Steering	48	0	0	0
	Synoptic	13	18	23	26

<u>NW Pacific</u>		<u>U</u>		<u>V</u>	
		CSU84 ₅₀₀	CSU84 ₂₀₀	CSU84 ₅₀₀	CSU84 ₂₀₀
<u>North</u>	Persistence	47	12	51	52
	Steering	0	49	2	1
	Synoptic	28	14	19	22
<u>On</u>	Persistence	19	14	36	46
	Steering	9	1	0	1
	Synoptic	35	52	35	27
<u>South</u>	Persistence	56	51	40	37
	Steering	0	0	0	0
	Synoptic	6	9	11	12

For the Atlantic, the variance reduction due to steering was overwhelming for the meridional motion (V) north of the ridge and for both components of motion on the ridge. For the NW Pacific, however, steering contributed little to the reduction of variance, with one exception. Nearly 50% of the variance of zonal motion was explained by 200 mb steering predictors north of the ridge.

A second surprise is the amount of variance reduction due to synoptic predictors as compared to persistence. With the exception of the south-of-ridge category, the synoptic predictors are responsible for as much, if not more, of the variance reduction as is persistence in both ocean basins. This certainly indicates the model's potential for predicting anomalous cyclone motion if an anomaly is present in the analysis or forecast fields.

4.4 Correlation Coefficient Fields

Figures 4.1 through 4.4 present the correlation coefficient fields between the 500 mb geopotential heights/sea level pressures and tropical cyclone motion in the Atlantic north of the ridge prior to the selection and removal of any predictors. Northward and eastward cyclone motions are positive. The correlation coefficient fields for the other two categories relative to the ridge are presented in Appendix B. Correlations between cyclone motion and the synoptic fields are stronger in the Atlantic basin than in any of the other basins.

For the south-of-ridge category the difference in the degree of correlation between the synoptic fields and cyclone motion for the Atlantic as compared to the Pacific is particularly striking. Again, the erratic motion of Pacific cyclones embedded in the monsoonal trough

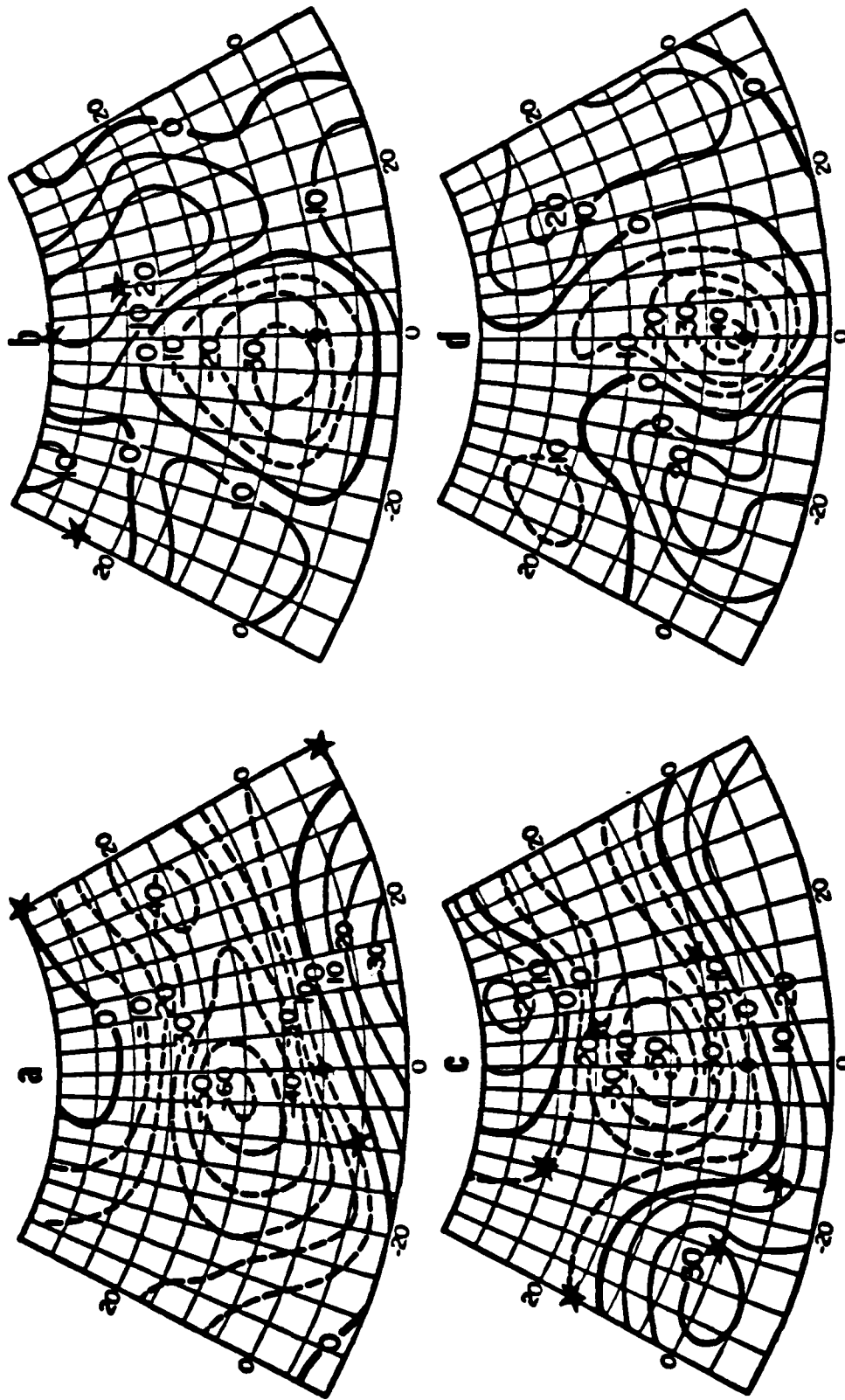


Fig. 4.1.1. Correlation coefficient fields ($\times .01$) for the Atlantic north-of-ridge fast U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (ϕ) and the stars indicate the gridpoints at which predictors were selected.

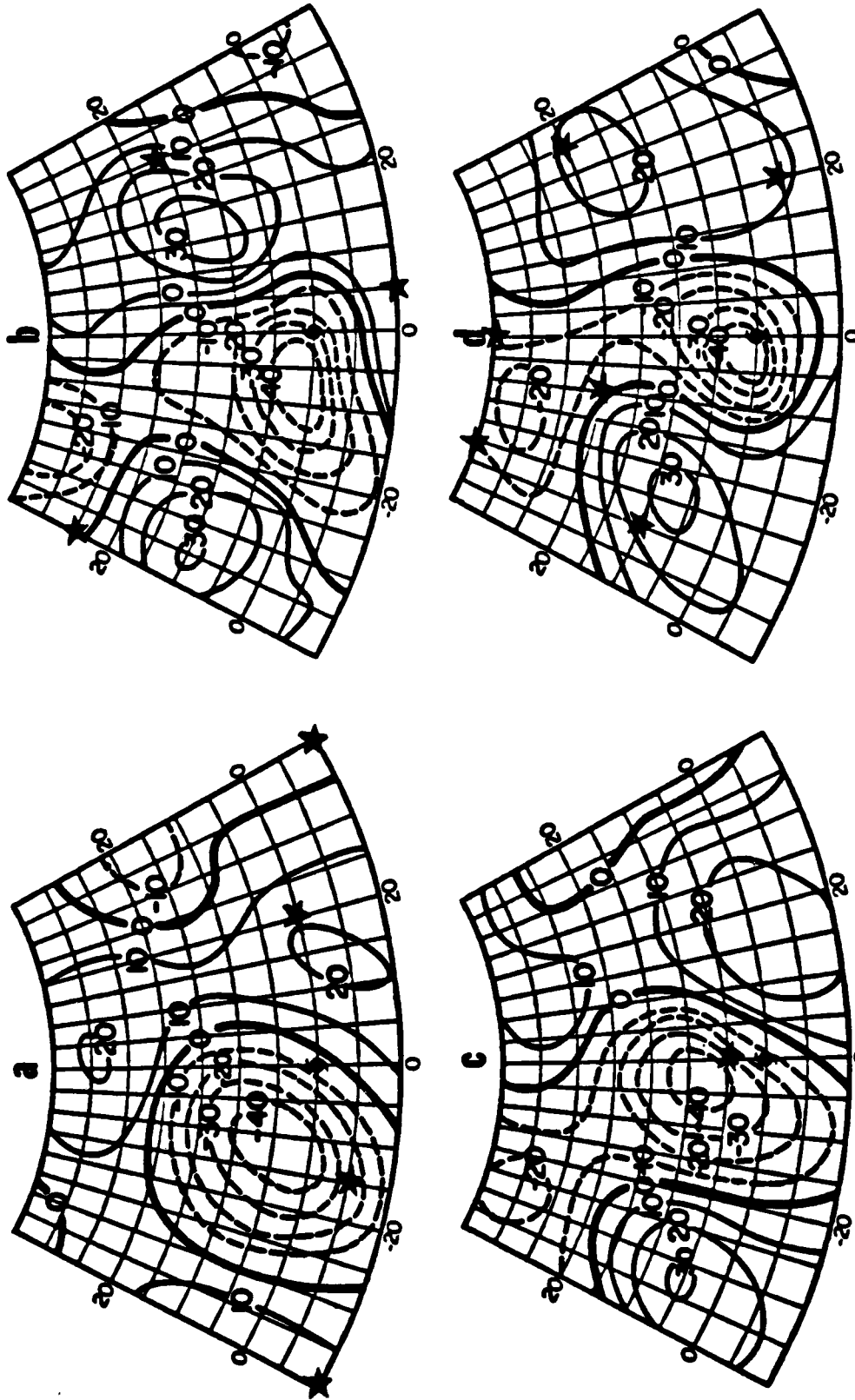


Fig. 4.2. Correlation coefficient fields ($\times .01$) for the Atlantic north-of-ridge fast V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\odot) and the stars indicate the gridpoints at which predictors were selected.

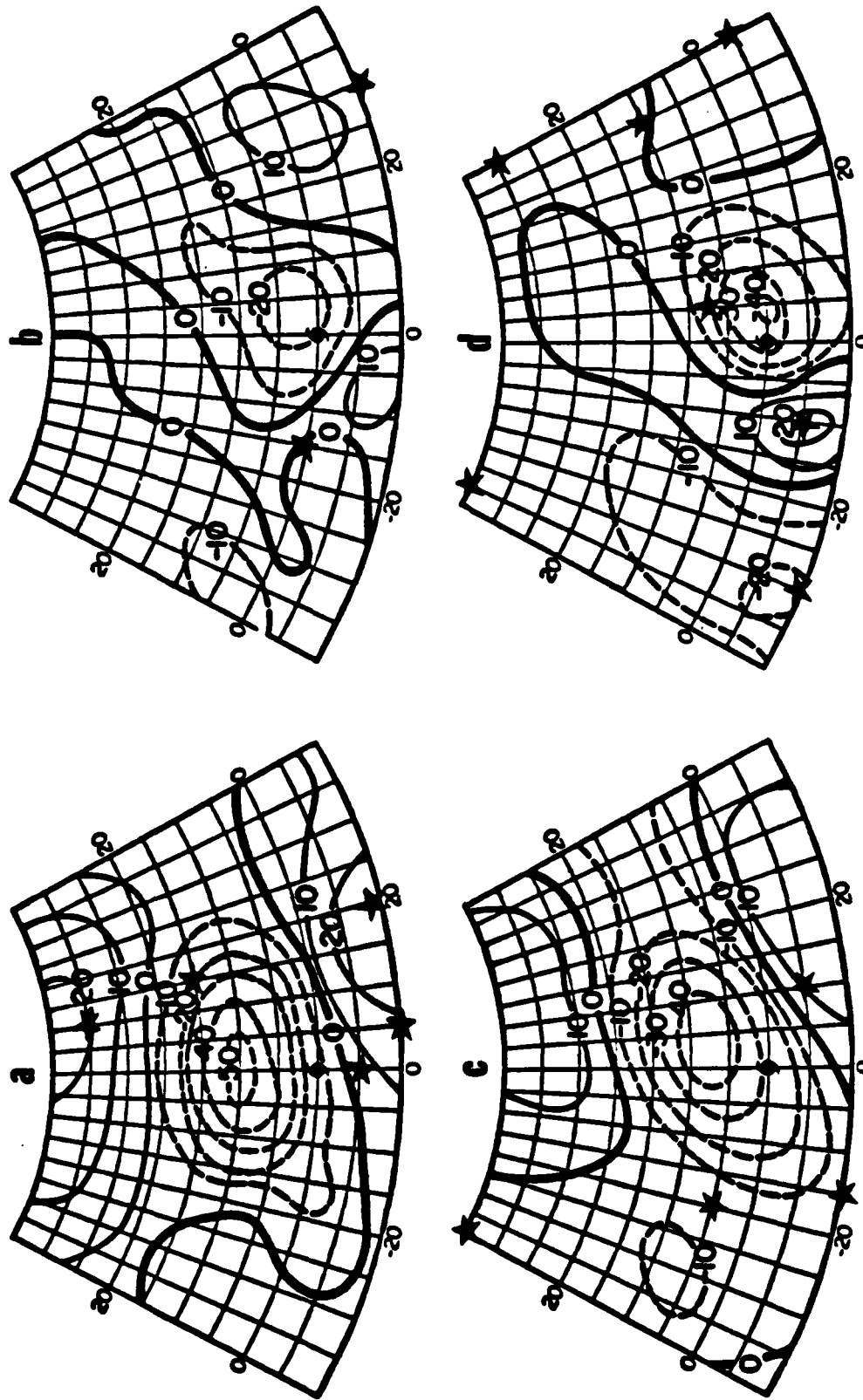


Fig. 4.3. Correlation coefficient fields ($\times .01$) for the Atlantic north-of-ridge slow U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

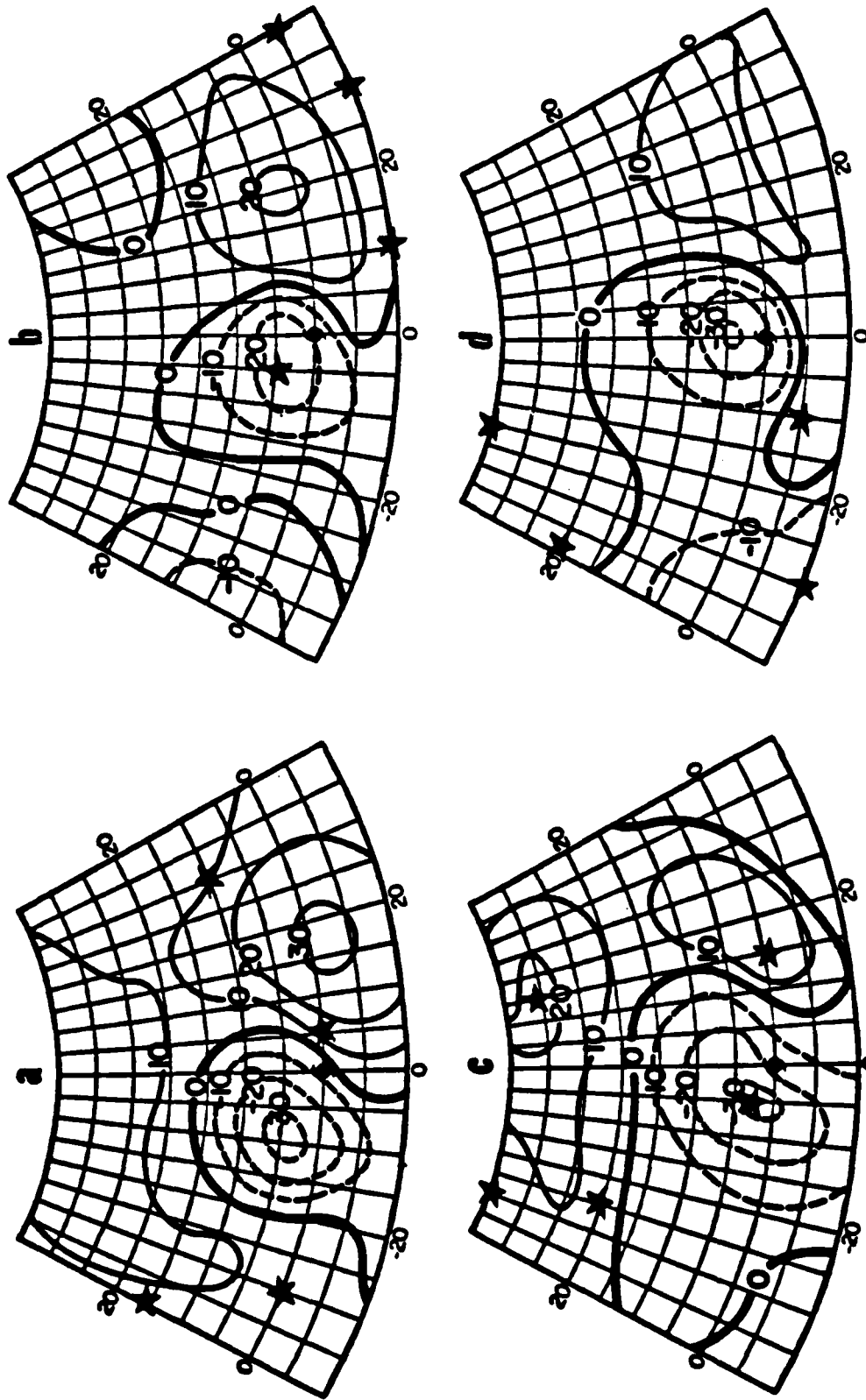


Fig. 4.4. Correlation coefficient fields ($\times .01$) for the Atlantic north-of-ridge slow V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\odot) and the stars indicate the gridpoints at which predictors were selected.

appears to account for the poor correlation of cyclone motion with the synoptic fields in the Pacific, especially south of the ridge.

In general, for the south-of-ridge category, above normal heights and pressures to the north are associated with westward motion (Figs. B.5 and B.7, panels a and c), and above normal heights and pressures to the east are associated with northward motion (Figs. B.6 and B.8, panels a and c). The 24-hour change or tendency fields (panels b and d), although weaker, imply the same correlation.

For the north-of-ridge category, there is again nothing unexpected in the figures. Eastward motion is associated with falling heights and pressures to the north (Figs. 4.1 and 4.3) and northward motion is associated with falling heights and pressures to the north and west (Figs. 4.2 and 4.4). The correlations are more concentrated with stronger gradients of correlation than for the south-of-ridge categories.

The ability of the screening process to pick out the subtle differences in the longitudinal position of the trough between the fast and slow cases is encouraging. Note that the centers of maximum correlation indicate that for the slow cases, the trough has already passed the cyclone and is located east of the cyclone. Compare the centers of maximum correlation relative to the cyclone for the four panels between Fig. 4.1 and 4.3.

For the on-the-ridge, the correlation fields are slightly more complex. In general, falling heights and pressures to the north and rising heights and pressures to the south are associated with eastward motion (Figs. B.1 and B.3); falling heights and pressures to the

west and rising heights and pressures to the east are associated with northward motion (Figs. B.2 and B.4).

Figures 4.5 through 4.8 present the correlation coefficient fields between the 500 mb geopotential heights/sea level pressures and tropical cyclone motion in the NW Pacific north of the ridge prior to the selection and removal of any predictors. The correlation coefficient fields for the other two categories relative to the ridge are presented in Appendix C. The relatively weak correlation between the synoptic fields and cyclone motion south of the ridge (Figs. C.5 through C.8) is to be noted. Most of the variance reducing potential comes from the 12-hour past motion. Synoptic information reduces the variance by only an additional 10%. This explains why statistical techniques such as HPAC that uses only climatology and persistence perform well in the low latitudes. The surprisingly weak correlation of cyclone motion to synoptic fields in this category for the NW Pacific can be explained by the presence of the near-equatorial monsoon trough in this part of the globe. When cyclones develop within this trough region, erratic motion is observed as the cyclones drift aimlessly due to the lack of any definite steering flow until they drift poleward and are picked up by the westerlies.

In general, correlations are similar to the Atlantic although there are differences. One of the most noticeable differences is the sea level pressure fields for the north-of-ridge category. Unlike the Atlantic, the strong correlation between low pressures to the north and eastward motion is missing. Refer to panel c on Figs. 4.5 and 4.7. Also missing is the strong correlation between low pressures to the northwest and northward motion. Refer to panel c on Figs. 4.6 and 4.8.

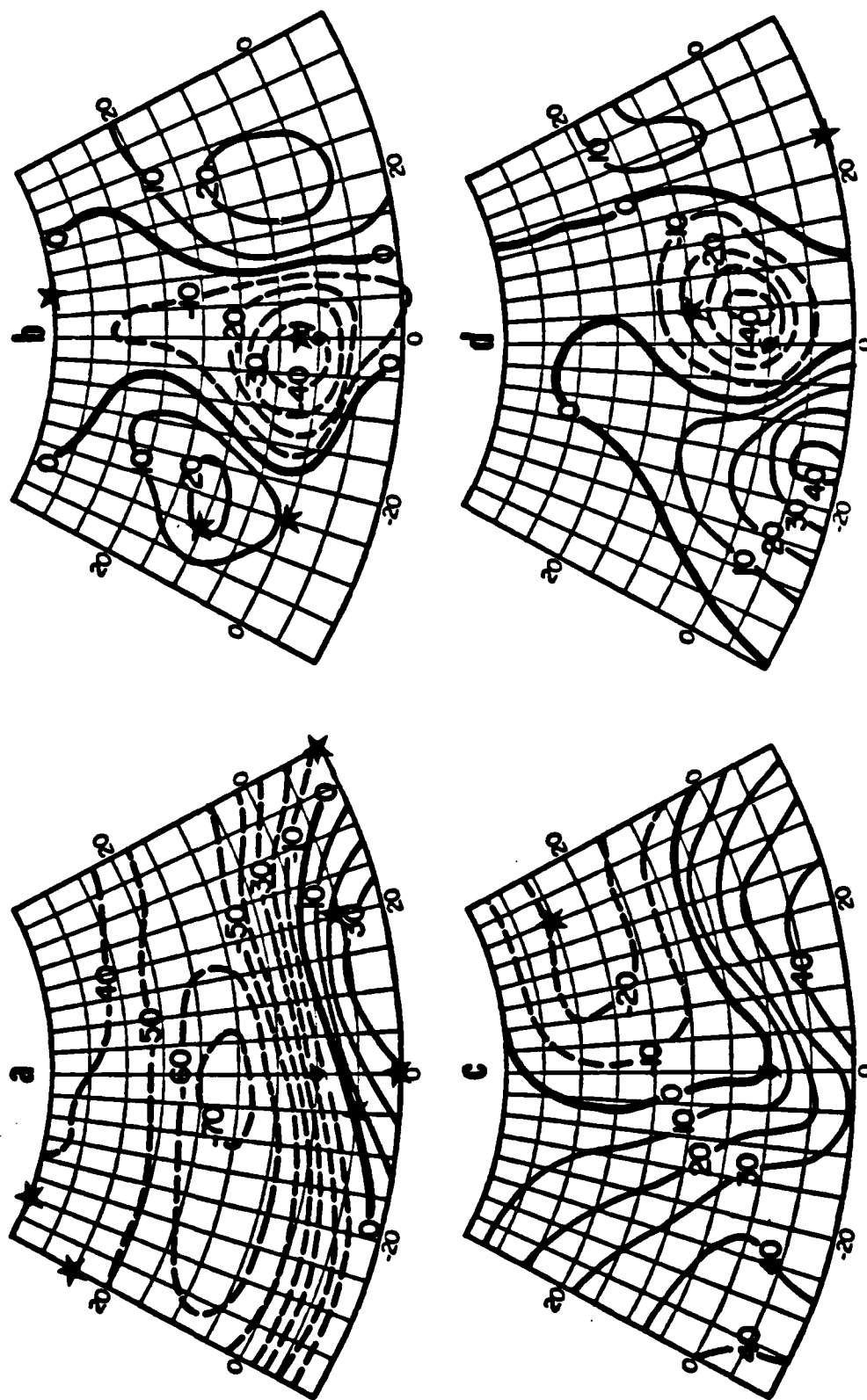


Fig. 4.5. Correlation coefficient fields ($\times .01$) for the NW Pacific north-of-ridge fast U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

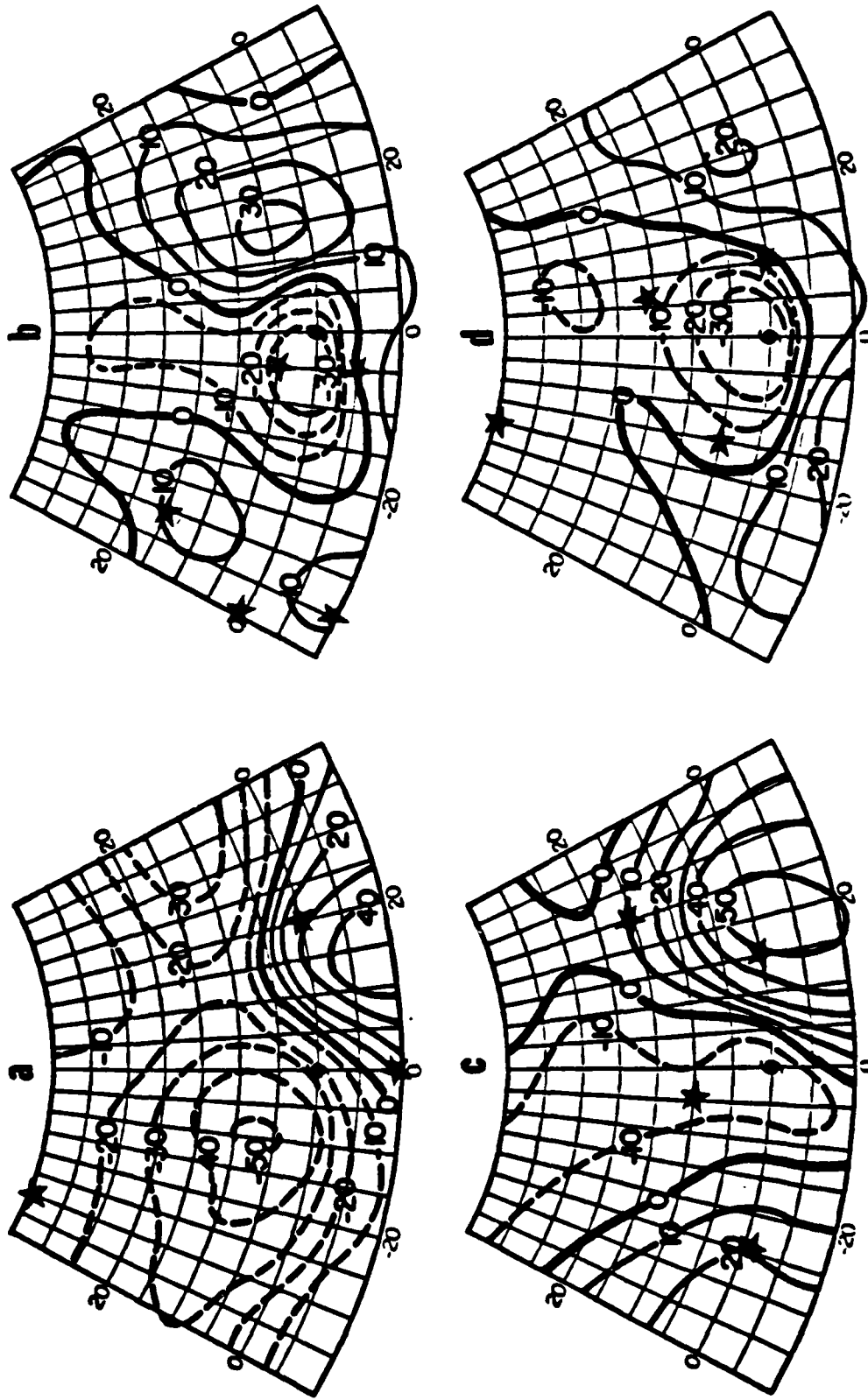


Fig. 4.6. Correlation coefficient fields ($\times .01$) for the NW Pacific north-of-ridge fast V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

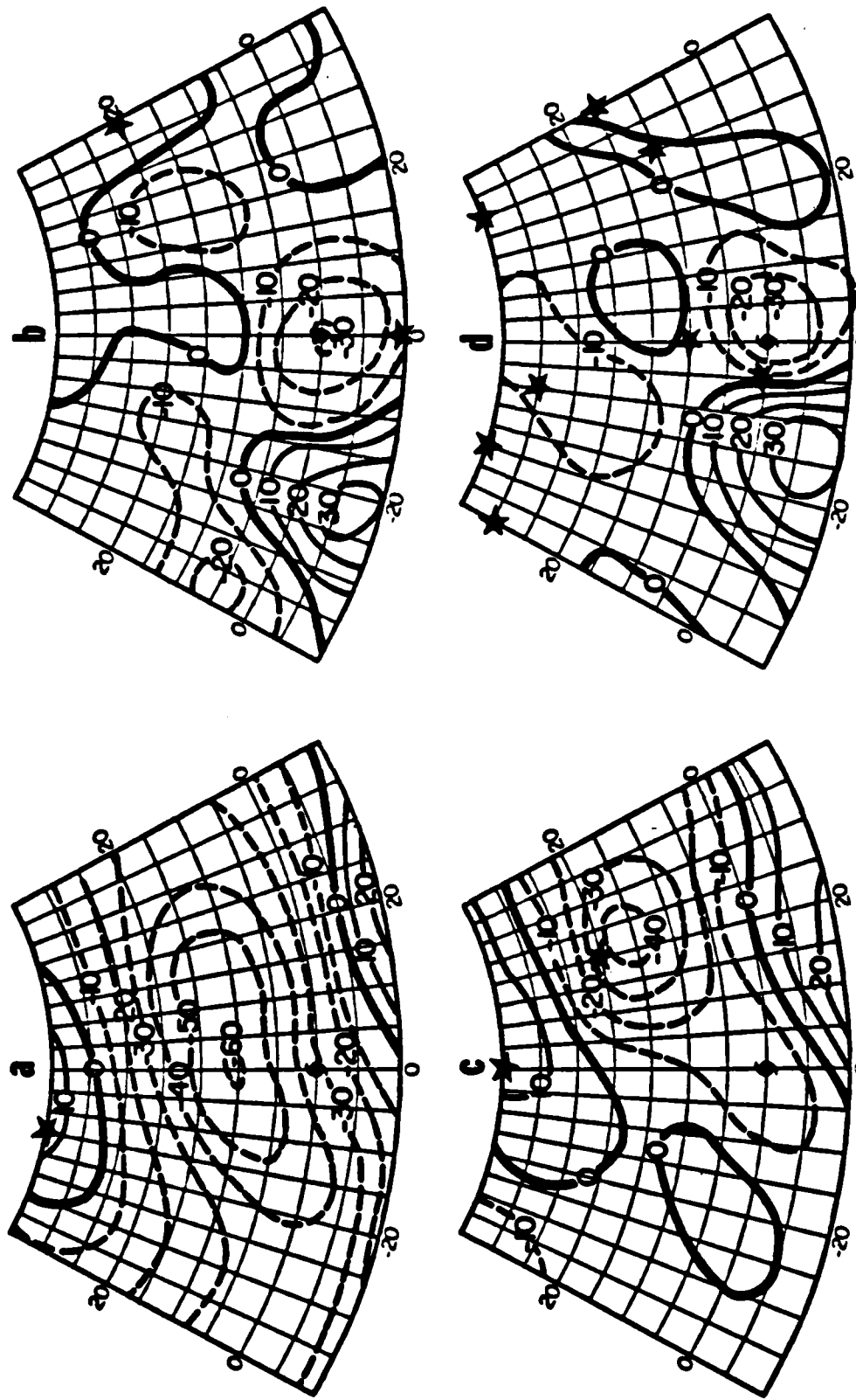


Fig. 4.7. Correlation coefficient fields ($\times .01$) for the NW Pacific north-of-ridge slow U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\odot) and the stars indicate the gridpoints at which predictors were selected.

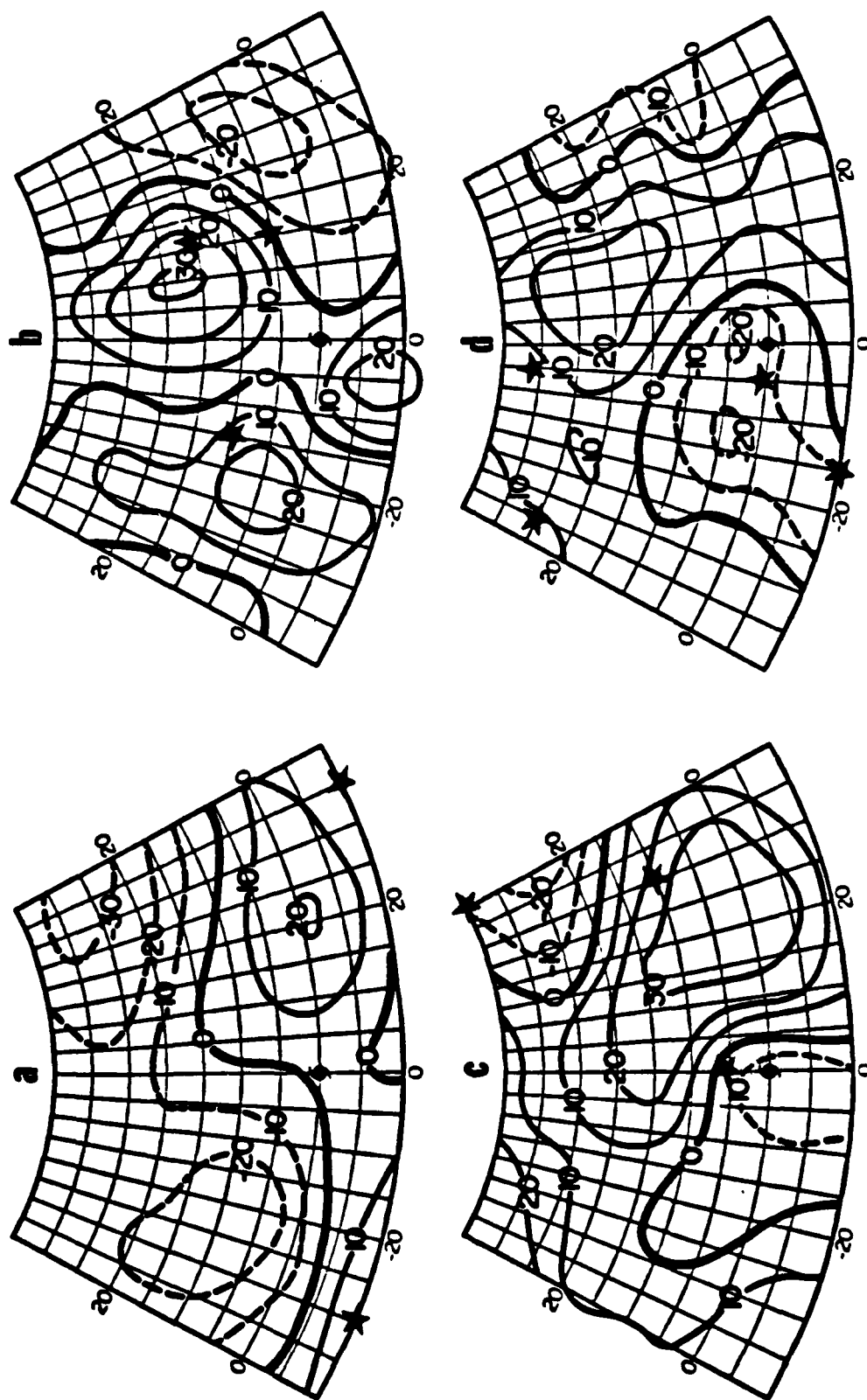


Fig. 4.8. Correlation coefficient fields ($\times .01$) for the NW Pacific north-of-ridge slow V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northwestward and eastward cyclone motions are positive. The position of the cyclone is denoted by (ϕ) and the stars indicate the gridpoints at which predictors were selected.

The strongest correlation occurs between the 500 mb heights and fast zonal motion for both north-of-ridge (Fig. 4.5 panel a) and on-the-ridge categories (Fig. C.1 panel a). Note that although the center of the strongest negative correlation 10° north-northwest of the cyclone center was selected as one of the predictors for fast zonal motion for the on-the-ridge category (Fig. C.1 panel a), the center of the strongest negative correlation 10° north of the cyclone center for the north-of-ridge category (Fig. 4.5 panel a) was not selected. The difference in the selection/non-selection is attributable to the order in which the predictors are selected. Recall that the correlation fields shown are the correlation prior to the selection and removal of any predictors. For the on-the-ridge category, the 500 mb height at the center of the strongest correlation was selected first while for the north-of-ridge category, other predictors such as steering and 24-hour height change were selected first. When this occurred, the residual that remained did not correlate well with the original height correlation field.

North Indian Ocean

Figures 4.9 and 4.10 present the correlation coefficient fields between the 500 mb geopotential heights/sea level pressures and tropical cyclone motion in the North Indian Ocean north of the ridge. The correlation fields for the other two categories relative to the ridge are presented in Appendix D. Correlations are not nearly as strong as in the other ocean basins, particularly south of the subtropical ridge as depicted by Figs. D.3 and D.4. Neither the 500 mb heights nor the sea level pressure correlate very strongly with cyclone motion south of the ridge. This explains the rather poor reduction in variance -- only 55% for zonal motion and 47% for meridional motion -- for this category

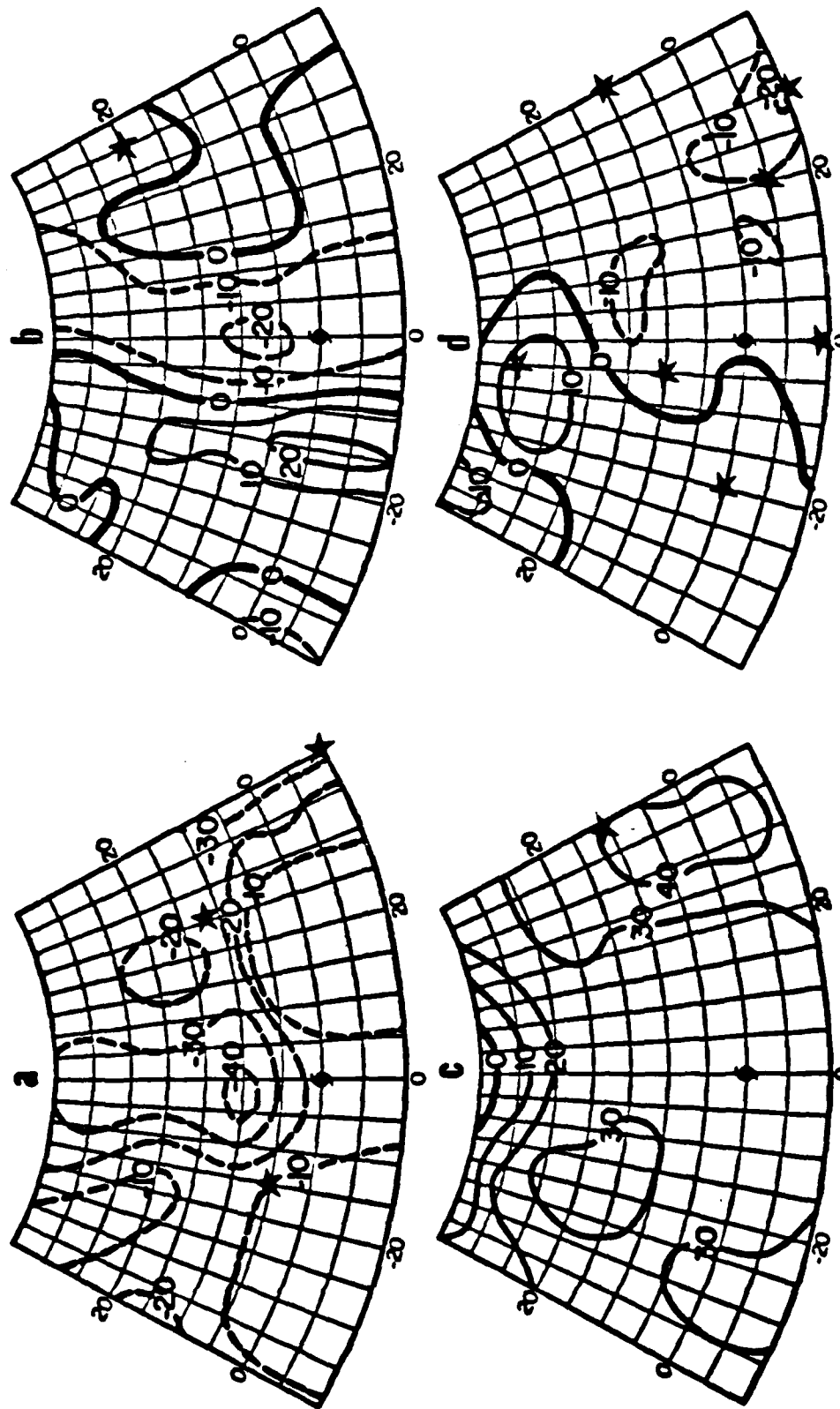


Fig. 4.9. Correlation coefficient fields ($\times .01$) for the North Indian Ocean north-of-ridge U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

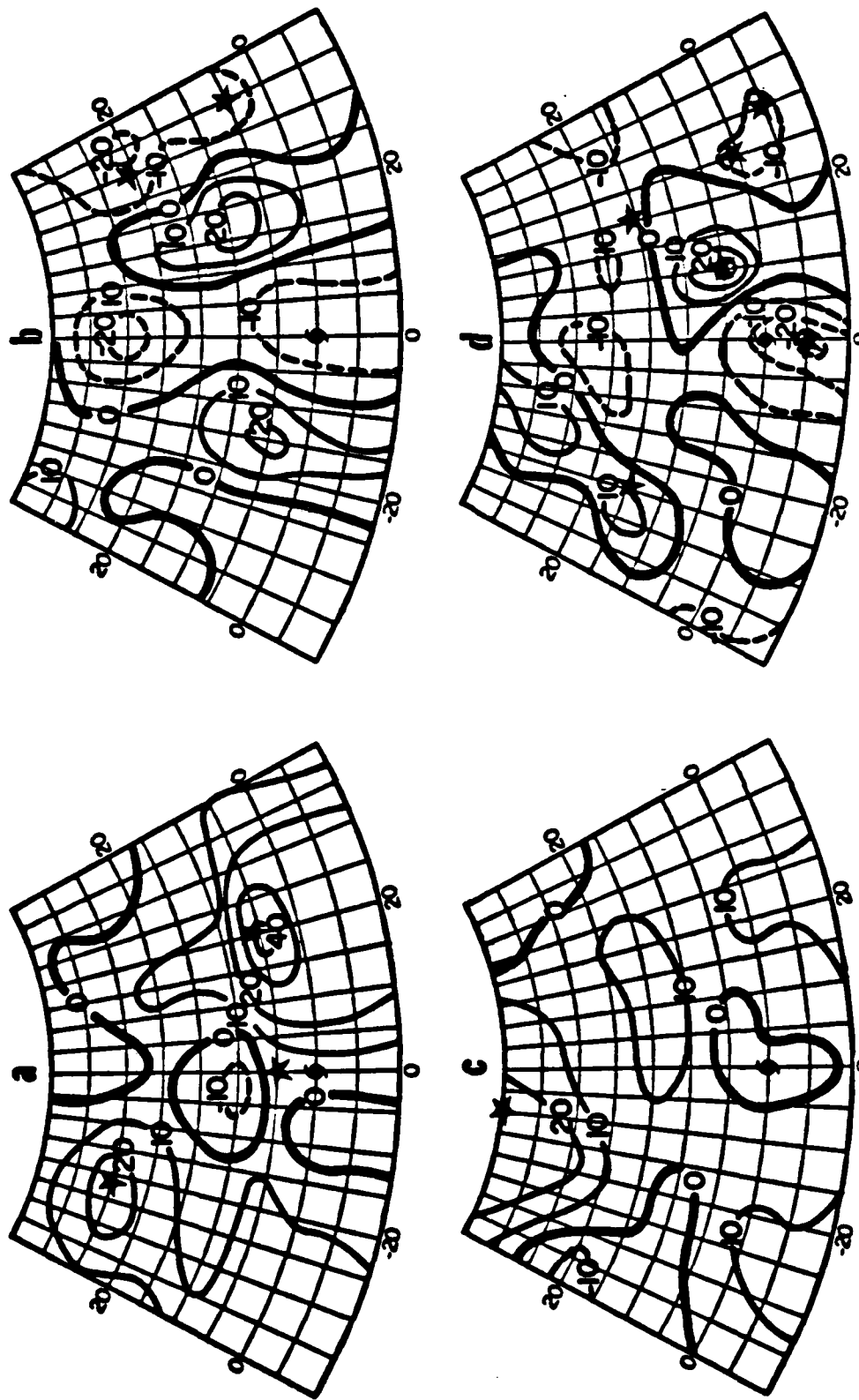


Fig. 4.10. Correlation coefficient fields ($\times .01$) for the North Indian Ocean north-of-ridge V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

of cyclones. Although the reduction in variance is relatively low, the forecast errors for the cyclones south of the ridge, as will be shown in the next chapter, are surprisingly small for both the dependent and independent set due to the small standard deviation. This is a result of the generally slow movement of these cyclone systems.

Strongest correlation for this ocean basin occurs between the 500 mb heights and zonal and meridional motion north of the ridge (panel a on Figs. 4.9 and 4.10). Again, the reason for the selection of the grid-point nearest the heights 20° east-northeast of the cyclone center that exhibited the strongest positive correlation with meridional motion north of the ridge and the non-selection of the grid-point nearest the heights 10° north of the cyclone center that exhibited strong negative correlation with zonal motion is due to the order of predictor selection.

In general, grid points near the centers of strongest positive or negative correlation were selected to provide height and pressure information to empirically predict 24-hour cyclone motion. Figure 4.10 shows a good example of the correlation field between 24-hour sea level pressure change and meridional motion north of the ridge. Refer to panel d on Fig. 4.10.

Table 4.5 illustrates the reduction of variance by the various predictors for the North Indian Ocean. Unlike the Atlantic and NW Pacific, steering does not contribute to cyclone motion except for a slight contribution to the zonal motion north of the ridge. Instead, it is the synoptic predictors, primarily the surface pressure tendencies, that play a significant role. With the exception of the south-of-ridge category, they are dominant. Such a large difference from the NW

TABLE 4.5

Percent of variance reduction by the various predictors for the North Indian Ocean. (X - persistence; H - 500 mb height; ΔH - 24-hour change of 500 mb height; P - surface pressure; ΔP - 24-hour change of surface pressure; S - steering at 500 mb).

<u>U</u>		<u>V</u>	
North (237 cases)	X = 31	X = 18 H = 17 ΔH = 7 P = 4 ΔP = 28 S = 0	56
	H = 5		
	ΔH = 4		
	P = 6		
	ΔP = 14		
	S = 14		
<hr/>			
On (188 cases)	X = 29	X = 32 H = 0 ΔH = 9 P = 0 ΔP = 18 S = 6	27
	H = 5		
	ΔH = 6		
	P = 14		
	ΔP = 21		
	S = 5		
<hr/>			
South (188 cases)	X = 41	X = 33 H = 5 ΔH = 1 P = 3 ΔP = 4 S = 1	13
	H = 7		
	ΔH = 2		
	P = 1		
	ΔP = 5		
	S = 1		

Pacific may explain why an attempt to use regression equations developed for NW Pacific cyclones failed when used for North Indian Ocean cyclones.

The screening process was terminated when a selected predictor contributed less than 1 percent to the reduction in the variance or when a maximum number of 20 predictors had been selected. As will be explained in Chapter 5, speed stratification failed to enhance the predictive skill of the model. As a result, the regression equations presented in this chapter apply to the model versions with no speed stratification.

Tables 4.6 through 4.8 list the selected predictors, the associated coefficients and the reduction of variance for the three stratified categories in the Atlantic. Similar information for the NW Pacific is presented in Tables 4.9 through 4.11. Tables 4.12 through 4.14 contain the list for the North Indian Ocean and Table 4.15 for the South China Sea.

Note that for all of the ocean basins, the majority of the selected synoptic predictors are located at grid points 15° or greater from the cyclone center. Many of them are located on the edge of the grid 40° from the cyclone. It was gratifying to observe that the large-scale circulation features were being incorporated into the model without explicitly forcing out of the regression any grid points near the cyclone.

Further, as many, if not more, 24-hour past changes of the 500 mb heights and sea level pressure were selected compared to the current heights or pressures. Apparently, by not using prognostic data prior to its valid time, the tendencies of heights and pressures were critical in determining how the current fields would evolve over the next 24 hours.

TABLE 4.6

Predictors, coefficients and reduction of variance for 24-hr U and V motion north-of-ridge for the Atlantic

	U		V	
	With 200 mb steering	With 500 mb steering	With 200 mb steering	With 500 mb steering
C ₀	-6405.097	546.603	-3159.411	2463.241
C ₁	.583 U ₋₁₂	-.457 H _{10,-5}	.377 Φ _{500v}	.434 Φ _{500v}
C ₂	-4.999 P _{10,0}	.662 U ₋₁₂	.304 V ₋₁₂	.365 V ₋₁₂
C ₃	.220 Φ _{200NW5u}	.557 H _{-10,15}	-.170 $\Delta\Phi$ _{200NSu}	.532 H _{-5,-40}
C ₄	3.103 P _{10,-30}	-.352 Δ H _{5,-5}	-7.026 P _{5,0}	-.195 $\Delta\Phi$ _{500NSu}
C ₅	.133 V ₋₂₄	-2.840 P _{10,-5}	.460 H _{-5,-35}	-5.107 P _{5,0}
C ₆	2.821 Δ P _{35,-30}	.519 Δ H _{-5,-5}	-.112 Φ _{200NW10-5u}	-.310 Δ H _{-5,-15}
C ₇	.583 H _{-10,15}	-1.178 Δ P _{30,40}	1.661 Δ P _{20,30}	1.314 Δ P _{20,25}
C ₈	1.731 P _{30,0}	1.313 Δ P _{30,10}	2.433 P _{0,15}	.578 H _{0,15}
C ₉	-.485 Δ P _{5,-5}	.707 H _{0,-5}	2.693 P _{10,-30}	1.999 Δ P _{15,-30}
C ₁₀	-2.112 H _{30,40}	7.014 Δ P _{-10,35}	-.237 Δ H _{0,-35}	-.130 Φ _{500NW10-5u}
C ₁₁	8.311 Δ P _{-10,35}	-1.491 Δ P _{10,35}	.417 H _{0,15}	-.562 H _{-10,5}
C ₁₂	-2.144 Δ P _{5,5}	-1.632 Δ P _{20,-35}	2.044 Δ P _{10,15}	-.166 Δ H _{10,-15}
C ₁₃	.169 Δ H _{10,10}	-.561 Δ H _{0,0}	-.464 Δ H _{-5,-15}	6.886 Δ P _{-5,-10}
C ₁₄	-3.821 Δ P _{0,20}	-.741 H _{-10,-10}	5.705 Δ P _{-5,-10}	-.080 H _{35,-35}
C ₁₅	2.712 P _{0,30}	.215 Δ H _{10,15}	.097 Δ H _{30,10}	-.220 Δ H _{-5,-40}
C ₁₆	.072 H _{30,40}	1.971 P _{25,-10}	-.348 Δ H _{5,-10}	-.324 Δ H _{5,0}
C ₁₇	1.475 Δ P _{25,30}	1.161 Δ P _{35,-30}	3.762 Δ P _{-5,20}	.063 $\Delta\Phi$ _{500N10v}
C ₁₈	-.117 Δ H _{10,-20}	-.074 Φ _{500N20u}	-5.302 Δ P _{-10,0}	-5.227 Δ P _{-10,0}
C ₁₉	-1.212 Δ P _{25,-30}		.296 Δ H _{-5,-5}	2.875 Δ P _{0,10}
C ₂₀	1.629 Δ P _{5,-40}		-.146 Δ H _{0,40}	
Reduction of variance	84%	83%	80%	78%

TABLE 4.7

Predictors, coefficients and reduction of variance for 24-hr U and V motion on-the-ridge for the Atlantic

	U		V	
	With 200 mb steering	With 500 mb steering	With 200 mb steering	With 500 mb steering
C ₀	-17982.797	-9051.025	-5549.292	-5865.584
C ₁	.308 Φ 500u	.301 Φ 500u	.359 Φ 500v	.443 Φ 500v
C ₂	.536 H _{0,5}	.188 V ₋₁₂	.454 V ₋₁₂	.369 V ₋₁₂
C ₃	.508 U ₋₁₂	.230 H _{5,-35}	.178 Δ Φ 200v	.224 Δ Φ 500N5v
C ₄	-.055 Δ Φ 200NW20v	-.186 H _{3,-10}	4.351 Δ P _{0,40}	10.424 Δ P _{-10,40}
C ₅	-.938 Δ H _{-10,-20}	-1.206 Δ P _{35,-35}	-2.210 Δ P _{5,-20}	-2.399 Δ P _{10,-20}
C ₆	9.708 P _{-5,25}	4.779 P _{0,40}	.955 H _{-10,-25}	.787 H _{0,-20}
C ₇	.958 Δ P _{30,30}	-1.371 Δ H _{-10,-25}	2.535 Δ P _{15,15}	-2.228 Δ P _{30,-20}
C ₈	.249 H _{15,-40}	.360 U ₋₁₂	-.087 Δ P _{15,15}	.285 Δ H _{20,10}
C ₉	.087 Φ 200NW15u	.319 H _{0,0}	-.240 U ₋₂₄	-.235 U ₋₂₄
C ₁₀	2.444 P _{35,-10}	1.980 P _{30,-35}	-.437 Δ H _{-10,10}	2.479 Δ P _{20,40}
C ₁₁	-.154 Δ H _{15,-35}	.128 Δ H _{30,20}	2.460 Δ P _{20,40}	-.714 Δ H _{0,-25}
C ₁₂	2.661 Δ P _{20,5}	-2.361 Δ P _{15,-20}	.126 Δ H _{30,-40}	.153 Δ H _{30,-40}
C ₁₃	3.834 P _{0,-35}	.794 Δ H _{5,-25}	-1.430 Δ P _{35,-20}	-.099 Φ 500NW20v
C ₁₄	-2.787 P _{10,25}	-8.626 Δ P _{-10,-10}	-.035 Φ 200NW20v	-.207 Δ H _{10,35}
C ₁₅	.149 Δ H _{20,20}	5.877 Δ P _{-5,-15}	-.515 Δ H _{0,-30}	3.476 P _{0,35}
C ₁₆	-3.878 Δ P _{5,20}	-.202 Δ H _{5,40}	-.372 Δ H _{-10,-10}	-.378 Δ H _{0,5}
C ₁₇	-1.689 Δ P _{15,-25}	-6.993 Δ P _{5,20}	.063 Φ 200N10-5v	-2.209 P _{10,0}
C ₁₈	.096 Δ H _{30,-40}	.239 Δ H _{10,20}	.261 Δ H _{0,-40}	6.095 Δ P _{-10,20}
C ₁₉	-2.834 Δ P _{10,0}	-.067 Δ H _{20,-15}	-.045 Φ 200N10-5u	
C ₂₀	5.173 Δ P _{-5,-15}			
Reduction of variance	83%	84%	88%	88%

TABLE 4.8

Predictors, coefficients and reduction of variance for 24-hr U and V motion south-of-ridge for the Atlantic

	U		V	
	With 200 mb steering	With 500 mb steering	With 200 mb steering	With 500 mb steering
C ₀	12.750	-1090.111	-9080.922	-3143.237
C ₁	.321 U ₋₁₂	.209 P _{500u}	.469 V ₋₁₂	.550 V ₋₁₂
C ₂	-.465 H _{15,-5}	.341 U ₋₁₂	.211 H _{15,5}	-.570 AH _{5,-15}
C ₃	-.376 AH _{10,5}	-4.807 AP _{5,10}	-.407 AH _{5,-20}	.207 H _{15,5}
C ₄	2.603 P _{15,-40}	.885 AP _{35,40}	.245 H _{-5,30}	9.816 AP _{5,15}
C ₅	-2.147 AP _{25,30}	2.342 P _{10,-35}	-1.149 AP _{30,-15}	.786 H _{-10,30}
C ₆	.635 P _{35,30}	-1.819 AP _{25,30}	10.404 AP _{5,15}	-1.235 AP _{30,-15}
C ₇	-.124 H _{25,-20}	1.197 P _{35,-35}	-1.112 AP _{-10,10}	-9.642 AP _{-10,10}
C ₈	.178 H _{10,-35}	-.430 H _{15,-10}	-6.875 AP _{5,-5}	-7.640 AP _{5,-5}
C ₉	-.264 H _{5,20}	-.480 AH _{10,5}	2.995 P _{15,0}	1.541 AP _{20,40}
C ₁₀	.674 AH _{-5,10}	.144 AH _{30,-35}	1.700 AP _{20,40}	-.701 H _{0,-5}
C ₁₁	.717 P _{35,-30}	-3.586 AP _{-5,0}	-1.197 P _{25,-10}	-.252 AH _{0,30}
C ₁₂	2.583 P _{15,20}	1.160 P _{30,25}	-3.636 AP _{0,-40}	4.315 AP _{0,-25}
C ₁₃	-.476 H _{10,5}	.253 H _{10,-30}	5.374 AP _{0,-25}	-.080 U ₋₁₂
C ₁₄	-5.704 AP _{5,10}	-.095 H _{25,-40}	-.742 H _{0,-5}	-.660 AH _{-5,-35}
C ₁₅	.827 H _{35,40}	-.666 H _{-10,-20}	.932 H _{-10,10}	2.436 P _{15,0}
C ₁₆		6.046 AP _{0,-25}	.163 H _{15,-35}	-1.002 P _{25,-10}
C ₁₇		-.338 AH _{10,-25}	-1.963 P _{15,-25}	6.834 AP _{-10,-5}
C ₁₈		-.112 V ₋₁₂	3.443 P _{0,5}	.180 AH _{10,-35}
C ₁₉		1.711 P _{10,-5}	1.040 P _{25,-40}	
C ₂₀		.354 AH _{-5,10}	-.082 AH _{20,-40}	
Reduction of variance	72%	73%	70%	69%

TABLE 4.9
Predictors, coefficients and reduction of variance for 24-hr U and V motion north-of-ridge for the NW Pacific.

	U		V	
	With 200 mb steering	With 500 mb steering	With 200 mb steering	With 500 mb steering
C ₀	2567.649	11215.979	-3371.009	108.378
C ₁	.191 Ψ_{500u}	.430 U ₋₁₂	.599 V ₋₁₂	4.427 $\Delta P_{-5,-35}$
C ₂	.484 U ₋₁₂	-.345 H _{15,0}	2.781 P _{15,25}	.552 V ₋₁₂
C ₃	-3.952 $\Delta P_{10,5}$	.205 V ₋₁₂	-.407 H _{10,-5}	1.776 P _{15,30}
C ₄	.847 H _{-5,15}	-4.643 P _{0,40}	.553 H _{0,35}	-8.952 P _{5,0}
C ₅	-5.038 P _{0,40}	.496 $\Delta H_{10,-30}$	-4.198 P _{10,-5}	8.643 P _{0,15}
C ₆	.448 $\Delta H_{10,-30}$	.698 H _{-5,10}	-.289 $\Delta H_{20,-15}$	.118 $\Delta \Psi_{500v}$
C ₇	-.548 H _{-10,-30}	-2.940 $\Delta P_{25,-40}$	-.479 $\Delta H_{5,-10}$	.400 H _{0,30}
C ₈	-.111 $\Psi_{200NW20v}$	-5.845 $\Delta P_{5,5}$	4.766 $\Delta P_{0,10}$	-.527 H _{5,-5}
C ₉	.224 V ₋₁₂	-.145 $\Delta H_{25,20}$	-.532 H _{-10,0}	5.029 P _{-10,40}
C ₁₀	9.023 $\Delta P_{-10,25}$	4.377 $\Delta P_{0,15}$	10.393 P _{-5,20}	-1.584 $\Delta P_{25,-20}$
C ₁₁	-2.589 $\Delta P_{25,-40}$	-.353 H _{-10,-30}	-4.958 P _{-5,40}	.072 $\Psi_{500N20v}$
C ₁₂	-.088 $\Delta \Psi_{200NW15u}$	.368 H _{0,35}	.106 $\Delta \Psi_{200N15u}$	.364 $\Delta H_{5,-25}$
C ₁₃	-1.899 P _{25,40}	-.300 H _{10,15}	-1.639 $\Delta P_{20,35}$	-4.057 $\Delta P_{5,-15}$
C ₁₄	-.198 Ψ_{500v}	-.757 H _{-10,40}	-.031 $\Psi_{200NW10-Su}$	-.437 $\Delta H_{0,30}$
C ₁₅	2.770 P _{15,-40}	2.004 $\Delta P_{35,-35}$	1.911 $\Delta P_{25,0}$	.174 $\Delta H_{10,40}$
C ₁₆	.230 $\Delta H_{35,-5}$	-1.495 $\Delta P_{10,5}$	-4.530 $\Delta P_{0,30}$	.692 $\Delta H_{-10,35}$
C ₁₇	-.068 $\Psi_{200N20u}$	-.929 P _{25,40}	.155 $\Delta H_{15,40}$	5.807 $\Delta P_{-10,20}$
C ₁₈	.222 $\Delta H_{15,40}$	.105 $\Delta H_{15,40}$	1.426 $\Delta P_{30,-40}$	4.216 P _{-5,0}
C ₁₉	-4.979 $\Delta P_{0,40}$	-2.804 $\Delta P_{10,0}$	1.568 P _{25,15}	-1.535 $\Delta P_{15,35}$
C ₂₀		-.072 $\Psi_{500NW10-Su}$	-.137 $\Delta H_{30,-35}$	.081 $\Delta \Psi_{500N10-Su}$
Reduction of variance	76%	75%	75%	73%

TABLE 4.10

Predictors, coefficients and reduction of variance for 24-hr U and V motion on-the-ridge for the NW Pacific

	U		V	
	With 200 mb steering	With 500 mb steering	With 200 mb steering	With 500 mb steering
C ₀	-7662.345	-3312.594	-4706.509	-4613.508
C ₁	-.464 H _{10,-5}	-.597 H _{5,-5}	.533 V ₋₁₂	-.055 H _{20,40}
C ₂	.302 U ₋₁₂	.319 U ₋₁₂	-.897 H _{5,-10}	.534 V ₋₁₂
C ₃	4.497 P _{-10,0}	.198 Φ _{500NW5u}	3.999 P _{0,40}	-1.025 H _{5,-10}
C ₄	-.261 H _{10,15}	-.130 H _{15,25}	-8.257 Δ P _{-10,-10}	5.968 P _{0,40}
C ₅	-.628 Δ H _{5,-10}	-.669 Δ H _{5,-10}	3.491 P _{-10,0}	-7.715 Δ P _{-10,-10}
C ₆	1.530 Δ P _{25,-35}	.191 V ₋₂₄	-1.430 Δ P _{20,-5}	-.191 Δ H _{20,-15}
C ₇	3.031 P _{-5,25}	6.560 Δ P _{-10,-30}	-.215 Δ H _{15,-25}	3.423 P _{-10,-40}
C ₈	8.773 Δ P _{-10,-30}	.401 H _{0,40}	4.691 Δ P _{5,15}	.092 H _{30,15}
C ₉	.349 H _{0,40}	5.444 P _{-10,-5}	-3.971 P _{5,-5}	-1.182 P _{30,10}
C ₁₀	-.892 Δ H _{-10,-10}	1.463 Δ P _{25,-5}	.291 H _{-10,-40}	-.124 U ₋₂₄
C ₁₁	.114 Δ H _{30,-15}	-2.644 Δ P _{10,15}	-.124 U ₋₂₄	-.290 Δ H _{15,-30}
C ₁₂	-2.928 Δ P _{10,20}	-.082 Δ H _{20,-5}	-.129 Δ P _{0,5}	2.851 Δ P _{5,15}
C ₁₃	1.920 P _{30,25}	1.603 Δ P _{30,-40}	4.703 P _{0,20}	-.090 Φ _{500N10-5u}
C ₁₄	.183 V ₋₂₄	.693 P _{35,35}	1.675 Δ P _{15,-40}	.374 H _{0,10}
C ₁₅	.062 Φ _{200u}	-3.718 Δ P _{-10,40}	-.120 Δ H _{15,20}	-.069 Δ H _{35,35}
C ₁₆	-1.332 Δ P _{35,25}	.200 Δ H _{25,-35}	-.076 Δ H _{35,30}	.180 Δ H _{15,-40}
C ₁₇	-.319 H _{0,-35}	-.168 H _{5,20}	.050 Δ P _{200v}	-5.257 Δ P _{-10,5}
C ₁₈	.369 H _{-5,-10}	.092 Δ P _{500N10-5v}	-.084 Δ H _{35,-30}	1.068 Δ P _{30,-40}
C ₁₉	-.059 Δ H _{25,35}	-.050 Δ H _{30,40}	-.035 Δ P _{200N10v}	4.664 Δ P _{0,-15}
C ₂₀	-.091 Δ H _{35,-25}		-3.980 Δ P _{-10,10}	-.229 Δ H _{10,-15}
Reduction of variance	67%	63%	74%	72%

TABLE 4.11
Predictors, coefficients and reduction of variance for 24-hr U and V motion south-of-ridge for the NW Pacific

	U		V	
	With 200 mb steering	With 500 mb steering	With 200 mb steering	With 500 mb steering
C ₀	2757.719	3133.007	-1500.630	-1280.997
C ₁	.594 U ₋₁₂	.604 U ₋₁₂	.499 V ₋₁₂	.506 V ₋₁₂
C ₂	-.476 H _{10,-10}	-.417 H _{10,-10}	.218 H _{15,5}	.257 H _{15,5}
C ₃	-.565 AH _{5,5}	-.508 AH _{5,5}	.044 AP _{500v}	2.465 AP _{5,15}
C ₄	-.094 V ₋₁₂	-.117 V ₋₁₂	-2.534 P _{0,-10}	-7.410 AP _{-10,-10}
C ₅	-2.222 AP _{15,10}	-1.327 AP _{15,10}	1.926 AP _{5,10}	.348 H _{-5,15}
C ₆	6.602 AP _{-10,10}	.059 H _{35,-20}	-5.799 AP _{-10,-10}	-.302 H _{5,-5}
C ₇	6.913 AP _{-10,-35}	5.807 AP _{-10,10}	-5.745 P _{-5,40}	.057 AH _{35,-35}
C ₈	-2.765 P _{0,-20}	.245 H _{5,-40}	-.131 H _{10,-30}	-.420 P _{35,15}
C ₉	.219 H _{5,-40}	-.437 P _{35,30}	.131 H _{5,20}	-.102 AH _{15,30}
C ₁₀	-.526 AP _{35,30}	6.250 AP _{-10,-35}	6.953 P _{-10,10}	-.179 AH _{15,-25}
C ₁₁	-3.323 AP _{5,-15}	-2.749 AP _{5,15}	.417 H _{-10,40}	4.560 P _{-5,10}
C ₁₂	.247 AH _{5,20}	-2.675 P _{5,25}	-.169 H _{5,0}	-1.651 P _{10,0}
C ₁₃	4.195 P _{-10,-10}	.266 AH _{5,20}	-.099 AP _{20,-25}	-2.944 P _{-10,40}
C ₁₄	.058 AH _{35,-15}	-.898 AP _{15,30}	1.056 AP _{15,20}	.247 AH _{-5,25}
C ₁₅	.196 AH _{5,-25}	-.090 H _{20,40}	3.356 AP _{-5,-30}	.150 AH _{5,-20}
C ₁₆	-.425 H _{-10,10}	1.477 P _{15,40}	-.543 AH _{-10,-10}	-.612 AH _{-10,-5}
C ₁₇	.084 AH _{25,-35}	5.361 AP _{-10,-10}	.296 AH _{-5,5}	.323 AH _{-5,5}
C ₁₈	-.815 AP _{15,30}	-.315 P _{30,-15}	-.074 AH _{25,-40}	.030 U ₋₁₂
C ₁₉	-.237 P _{35,40}	-2.094 AP _{5,5}	.026 H _{35,-40}	
C ₂₀	3.619 AP _{-10,-20}			
Reduction of variance	61%	63%	50%	51%

TABLE 4.12

Predictors, coefficients and reduction of variance for 24-hr U and V motion for north-of-ridge category for the North Indian Ocean

	<u>U</u>	<u>V</u>	
C ₀	-624.6672	-5654.0409	
C ₁	.3538	.3653	V ₋₂₄
C ₂	.2334	1.3532	H _{5,20}
C ₃	-.2209	-16.2332	AP _{0,25}
C ₄	3.3336	28.7486	AP _{5,10}
C ₅	-22.4239	-23.9050	AP _{-5,0}
C ₆	-.4186	1.4433	P _{35,-10}
C ₇	10.1656	7.2717	AP _{15,-25}
C ₈	7.9597	-.7670	ΔH _{20,30}
C ₉	-7.9171	-.8584	ΔH _{5,35}
C ₁₀	6.1242	-.8325	H _{5,0}
C ₁₁	.5001	15.1203	AP _{-5,35}
C ₁₂	-.6807	.2050	H _{25,-20}
C ₁₃	1.9375	-4.5111	AP _{15,20}
C ₁₄	11.8670		
C ₁₅	-.2813		
Reduction of variance	72%	74%	

TABLE 4.13

Predictors, coefficients and reduction of variance for 24-hr U and V motion for on-the-ridge category for the North Indian Ocean

	<u>U</u>		<u>V</u>
C ₀	-12198.8993		60.1728
C ₁	.4841	U ₋₁₂	.4757
C ₂	9.7347	P _{-10,-35}	3.0908
C ₃	-4.3658	ΔP _{15,-25}	-2.7541
C ₄	16.7942	ΔP _{-5,-35}	.4747
C ₅	-.2266	ΔH _{10,5}	.2503
C ₆	-.1340	Φ _{500N15u}	7.3980
C ₇	-.2141	ΔH _{35,-30}	-7.0843
C ₈	3.2214	ΔP _{10,40}	-1.4414
C ₉	-4.7700	ΔP _{15,5}	.2748
C ₁₀	-12.3065	ΔP _{-10,20}	-.2725
C ₁₁	.1666	H _{25,-30}	4.6092
C ₁₂	.3422	ΔH _{5,20}	
C ₁₃	2.8396	P _{15,-15}	Φ _{500NW10-5v}
C ₁₄	-6.2172	ΔP _{10,-15}	ΔH _{25,-15}
C ₁₅	-1.3645	P _{30,-5}	ΔH _{15,30}
C ₁₆	-1.0431	ΔΦ _{500N5v}	ΔP _{5,5}
Reduction of variance	78%		64%

TABLE 4.14

Predictors, coefficients and reduction of variance for 24-hr U and V motion for south-of-ridge category for the North Indian Ocean

	<u>U</u>		<u>V</u>
C ₀	3964.4589	-5666.9895	
C ₁	.4558	.4760	V ₋₁₂
C ₂	-.1678	.1193	H _{15,-35}
C ₃	-2.3967	5.3690	P _{-10,15}
C ₄	.2793	.0677	Q _{500v}
C ₅	-1.7260	-1.0161	AP _{25,-25}
C ₆	-.1471	.1604	H _{15,40}
C ₇	-2.5425	-3.8486	AP _{5,-5}
C ₈	.1774	1.2326	AP _{15,20}
C ₉	7.8780	-.1779	ΔH _{5,-30}
C ₁₀	-.1105	4.9715	AP _{-10,10}
C ₁₁	-.1317	.0720	ΔH _{25,-5}
C ₁₂	-1.8571	-.1533	H _{10,30}
C ₁₃	-.0426	-.1174	H _{5,0}
C ₁₄	.2052	-.0525	ΔH _{30,40}
C ₁₅	-2.4812	.0430	H _{30,25}
C ₁₆	2.8158		
C ₁₇	.0634		
C ₁₈	-.3391		
Reduction of variance	55%	47%	

TABLE 4.15
Predictors, coefficients and reduction of variance for 24-hr U and V motion for the South China Sea

	U	V
C ₀	8527.1815	-5663.1231
C ₁	.6418	.5828
C ₂	-17.7580	-.7670
C ₃	-.2903	-.3961
C ₄	-6.3370	.2340
C ₅	-.3097	-.2470
C ₆	-.5059	-6.6187
C ₇	.3005	1.1260
C ₈	-18.2355	.0885
C ₉	.1847	.7478
C ₁₀	-.8846	.2838
C ₁₁	1.3212	-.2859
C ₁₂	12.2946	-.3903
C ₁₃	-1.1634	-.1546
C ₁₄	-.6791	-.2778
C ₁₅	.2789	.2429
C ₁₆	-.2503	-18.3805
C ₁₇	.5709	.3540
C ₁₈	-13.3370	-1.2444
C ₁₉	1.1094	.0619
C ₂₀	-2.6403	
Reduction of variance	82%	64%

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CYCLONE TRACK PREDICTION(U) AIR FORCE INST OF TECH
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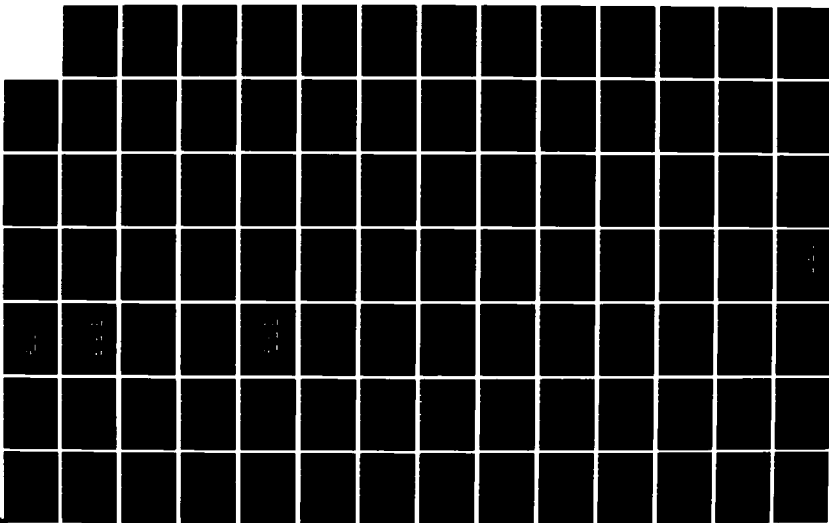
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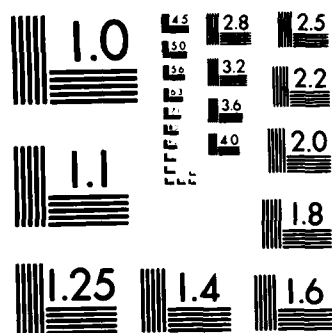
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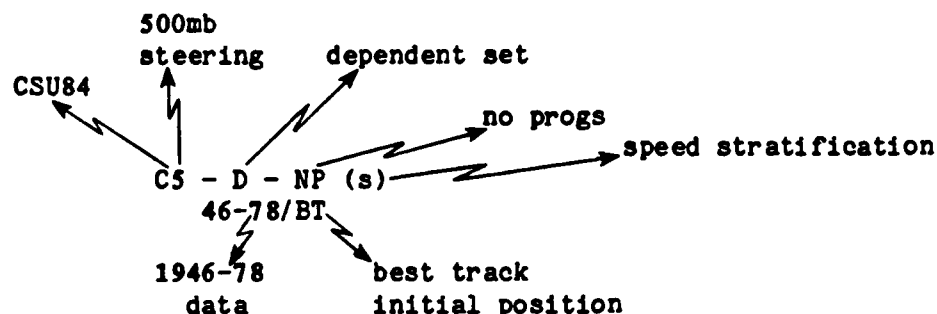


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5. VERIFICATION AND RESULTS

5.1 Atlantic

For easy reference, Table 5.1 presents a complete list of the various model runs that were performed with Atlantic cyclones. The symbolic name for each run was selected to easily denote the key elements for each particular model run. For example, the first run is deciphered as:



For each run, one or more of the following elements were changed:

- 1) 500 mb or 200 mb steering level (5 or 2)
- 2) dependent or independent data set or both combined
- 3) perfect-prog (PP) (verifying analyses), actual progs (AP) or no progs (NP)
- 4) speed stratification (s) or no speed stratification (blank)
- 5) data period of 1946-78, 1962-81, 1968-81, 1973-79, or 1979-81
- 6) best track (BT) initial positions or perturbed best track (PT) initial positions.

All of the forecast displacement errors referred to in this paper are in nautical miles (n mi) and this mean vector error (great-circle distance between the forecast and the actual location) was computed using the following formula:

$$E = \cos^{-1} [\sin XLAT \times \sin FLAT + \cos XLAT \times \cos FLAT \times \cos (XLON - FLON)] \times 60$$

TABLE 5.1

List of the various model runs for the Atlantic. Note that the symbolic name for each run denotes the level of the steering predictors, dependent or independent set, perfect-prog (PP) or actual prog (AP), speed stratification, data period, and best track (BT) initial position or perturbed (PT) best track initial position to simulate a pseudo-warning position.

CSU84 Model Runs	Steering Level	Dependent (D) or Independent (I)	Perfect-Prog(PP) Actual Prog (AP) No prog (NP)	Speed Stratification	Data Period	Initial Position
C5-D-NP(s) 46-78/BT	500 mb	D	NP	YES	1948-78	Best Track (BT)
C5-D-PP(s) 46-78/BT	500 mb	D	PP	YES	1948-78	BT
C5-D-PP(s) 62-81/BT	500 mb	D	PP	YES	1962-81	BT
C2-D-PP(s) 62-81/BT	200 mb	D	PP	YES	1962-81	BT
C2-D-PP 62-81/BT	200 mb	D	PP	NO	1962-81	BT
C5-D-PP 62-81/BT	500 mb	D	PP	NO	1962-81	BT
C5-I-PP(s) 62-81/BT	500 mb	I	PP	YES	1962-81	BT
C2-I-PP(s) 62-81/BT	200 mb	I	PP	YES	1962-81	BT
C5-I-PP 62-81/BT	500 mb	I	PP	NO	1962-81	BT
C2-I-PP 62-81/BT	200 mb	I	PP	NO	1962-81	BT

TABLE 5.1 (cont'd)

CSU84 Model Runs	Steering Level	Dependent (D) or Independent (I)	Perfect-Prog (PP) Actual Prog (AP) No Prog (NP)	Speed Stratification	Data Period	Initial Position
C2-D-PP 73-79/BT	200 mb	D	PP	NO	1973-79	BT
C2-I-PP 73-79/BT	200 mb	I	PP	NO	1973-79	BT
C5-DI-PP 68-81/BT	500 mb	D+I	PP	NO	1968-81	BT
C5-DI-AP 68-81/BT	500 mb	D+I	AP	NO	1968-81	BT
C5-DI-AP 68-81/PBT	500 mb	D+I	AP	NO	1968-81	Perturbed BT(PBT)
C5-I-PP 68-81/BT	500 mb	I	PP	NO	1968-81	BT
C5-DI-PP 73-79/BT	500 mb	D+I	PP	NO	1973-79	BT
C5-DI-AP 73-79/BT	500 mb	D+I	AP	NO	1973-79	BT
C5-DI-AP 73-79/PBT	500 mb	D+I	AP	NO	1973-79	PBT

where XLAT and XLON are the best track latitude and longitude and FLAT and FLON are the forecast latitude and longitude. The result of the verification on the dependent data set used to develop the regressions for the Atlantic is shown in Tables 5.2 and 5.3. The three model runs shown in Table 5.2 used 500 mb steering predictors instead of 200 mb steering predictors with the cases categorized with respect to the subtropical ridge and further stratified into fast and slow subsets based on the 500 mb height patterns. C5-D-NP(s)/(46-78/BT) is the traditional or classical approach of applying different regression equations for each of the three cyclone displacements -- 0 to 24, 0 to 48, and 0 to 72. For the synoptic predictors, each of the equations use only the current and 24-hour old analyses with no prognostic data. C5-D-PP(s)/(46-78/BT) used the same data set as C5-D-NP(s)/(46-78/BT) and introduced the new approach of segmenting the forecast motion into three 24-hour steps. It applied the same regression equations three times as the forecast positions were stepped forward. It used perfect prog data to update the synoptic predictors relative to the new cyclone position at the 24-hour and 48-hour forecast positions. C5-D-PP(s)/(62-81/BT) applied the same technique as C5-D-PP(s)/(46-78/BT) to a smaller, more recent data set for the purpose of comparing with a version using 200 mb steering since 200 mb data were available only since 1962. A run similar to C5-D-PP(s)/(62-81/BT) using 200 mb steering predictors instead of 500 mb steering predictors is shown in Table 5.3 as C2-D-PP(s)/(62-81/BT)

This decision to limit the development data to those after 1961 turned out to be very fortuitous since the results indicate that the largest overall decrease in error occurred between model runs

TABLE 5.2

Forecast errors (n mi) using 1946-78 dependent set for the no-prog classical method of regressing from the initial position to the forecast position; i.e., 0-24, 0-48, 0-72 (C5-D-NP(s)/(46-78/BT)), the perfect-prog new method of segmenting the 72-hour forecast period into three 24-hour segments (C5-D-PP(s)/(46-78/BT)), and the perfect-prog new method using a more recent development set (C5-D-PP(s)/(62-81/BT)). The number of verifying cases are in parentheses.

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	24-HR			48-HR			72-HR		
	C5-D-NP(s) 46-78/BT	C5-D-PP(s) 46-78/BT	C5-D-PP(s) 62-81/BT	C5-D-NP(s) 46-78/BT	C5-D-PP(s) 46-78/BT	C5-D-PP(s) 62-81/BT	C5-D-NP(s) 46-78/BT	C5-D-PP(s) 46-78/BT	C5-D-PP(s) 62-81/BT
<u>North</u>									
Fast	120(185)	109(253)	73(98)	250(185)	217(228)	139(84)	405(185)	343(227)	258(80)
Slow	120(357)	133(397)	76(151)	245(357)	218(408)	131(148)	370(357)	285(377)	161(143)
Total	120(542)	124(650)	75(249)	247(542)	217(636)	134(262)	382(542)	307(604)	196(223)
<u>On</u>									
Fast	90(186)	85(246)	96(80)	197(186)	167(232)	166(79)	349(186)	290(223)	242(65)
Slow	71(165)	75(201)	80(83)	164(165)	184(197)	145(66)	277(165)	302(187)	223(63)
Total	81(351)	80(447)	88(163)	182(351)	174(429)	156(145)	315(351)	295(410)	232(128)
<u>South</u>									
Fast	74(497)	73(397)	51(139)	162(497)	148(400)	103(136)	262(497)	216(380)	155(129)
Slow	74(435)	70(351)	63(135)	148(435)	146(330)	110(133)	245(435)	230(327)	152(134)
Total	74(932)	72(748)	57(274)	155(932)	147(730)	107(269)	254(932)	227(707)	153(263)
<u>All</u>	89(1825)	92(1845)	71(686)	188(1825)	179(1795)	127(646)	304(1825)	270(1721)	185(614)

TABLE 5.3

Speed versus no speed stratification runs. Forecast errors (n mi) for speed stratification run (C2-D-PP(s)/(62-81/BT)) using 200 mb steering is compared to runs without speed stratification using 200 mb steering (C2-D-PP/(62-81/BT)) and 500 mb steering (C5-D-PP/(62-81/BT)) for the years 1962-81. Number of cases are in parentheses.

<u>24-HR</u>			<u>48-HR</u>			<u>72-HR</u>			
<u>North</u>	<u>C2-D-PP(s)</u>	<u>C2-D-PP</u>	<u>C5-D-PP</u>	<u>C2-D-PP(s)</u>	<u>C2-D-PP</u>	<u>C5-D-PP</u>	<u>C2-D-PP(s)</u>	<u>C2-D-PP</u>	<u>C5-D-PP</u>
Fast	134(80)	---	---	157(65)	---	---	249(58)	---	---
Slow	90 (160)	---	---	186(153)	---	---	241(149)	---	---
Total	105(240)	86(242)	94(312)	177(218)	160(219)	183(291)	244(207)	227(206)	264(280)
<u>On</u>									
Fast	101(81)	---	---	176(74)	---	---	242(67)	---	---
Slow	92(74)	---	---	141(61)	---	---	215(57)	---	---
Total	97(155)	84(159)	60(170)	160(135)	144(139)	117(145)	230(124)	211(124)	192(124)
<u>South</u>									
Fast	73(184)	---	---	147(186)	---	---	218(173)	---	---
Slow	77(86)	---	---	132(77)	---	---	205(88)	---	---
Total	74(270)	65(274)	66(284)	143(263)	120(267)	120(277)	213(261)	178(261)	167(269)
<u>All</u>	90(665)	77(675)	76(766)	159(616)	139(625)	145(713)	227(592)	202(591)	212(673)

C5-D-PP(s)/(46-78/BT) and C5-D-PP(s)/(62-81/BT). This surprising result indicates that either the best track cyclone positions or the analysis fields or both for the early pre-satellite years are not up to the quality of those since the early 60's or that the statistical characteristics of the analyses suffered a drastic change somewhere between the early and later years.

A likely source of the difference in the analyses may stem from the implementation of the Cressman (1959) scan analysis method at the National Meteorological Center (NMC) in 1959. Similar data base inhomogeneities may occur on analyses after 1978 due to the Cressman analysis method being replaced by the 'first-guess'/spectral analysis PE hemispheric prognosis package in 1979. Neumann, et al. (1979) cites substantial deterioration in the performance of NHC statistical-synoptic and statistical-dynamical models, particularly NHC73, due to changes in the tropical analysis error characteristics.

Another surprising discovery occurred when the independent set was being verified. Because of the small sample sizes in some of the categories, a version of the model without any speed stratification was developed on the 1962-1981 dependent set. This version, with either 200 mb or 500 mb steering predictors, appears as model runs C2-D-PP/(62-81/BT) and C5-D-PP/(62-81/BT) respectively in Table 5.3. From the results, it is obvious that the speed stratification used in this model failed to enhance its predictive skill in any of the categories. In fact, Table 5.4, which presents the results of the verification on the independent set, reveals the superior skill of the model with no speed stratification. Compare, for example, model runs C5-I-PP(s) with

TABLE 5.4

Speed versus no speed stratification runs. Forecast errors (n mi) with independent data for the speed stratification runs using 500 mb steering (C5-I-PP(s)/(62-81/BT)) and 200 mb steering (C5-I-PP(s)/(62-81/BT)) are compared with runs with no speed stratification using 500 mb steering (C5-I-PP/(62-81/BT)) and 200 mb steering (C2-I-PP/(62-81/BT)). Number of cases are in parentheses. All runs were for the years 1962-81 with the use of Best Track.

	24-HR			48-HR			72-HR		
	C5-I-PP(s)	C2-I-PP(s)	C5-I-PP(C2-I-PP(C5-I-PP(C5-I-PP(s)	C2-I-PP(s)	C5-I-PP(s)	C2-I-PP(s)	C5-I-PP(s)	C2-I-PP(s)	
North									
Fast	139(42)	148(41)	---	268(29)	271(33)	---	404(27)	387(30)	
Slow	119(39)	126(40)	---	224(33)	192(28)	---	306(21)	246(17)	
Total	130(81)	137(81)	121(81) 115(81)	244(62)	235(61)	234(61) 191(60)	361(48)	336(47)	
							358(45)	281(44)	
On									
Fast	141(22)	102(29)	---	169(27)	167(28)	---	246(24)	212(25)	
Slow	92(24)	131(16)	---	190(11)	192(09)	---	300(08)	213(06)	
Total	115(46)	113(45)	96(46) 82(45)	175(38)	173(37)	158(38) 152(37)	259(32)	212(31)	
							212(32)	198(30)	
South									
Fast	90(79)	101(117)	---	184(73)	223(101)	---	283(70)	350(91)	
Slow	106(72)	104(34)	---	194(64)	162(34)	---	283(54)	212(31)	
Total	98(151)	102(151)	86(151) 84(151)	188(137)	208(135)	167(137) 164(136)	283(124)	315(122)	
							248(124)	252(123)	
All									
	110(278)	114(277)	98(278) 93(277)	201(237)	209(233)	183(236) 169(233)	297(204)	304(200)	
							267(201)	250(197)	

C5-I-PP and runs C2-I-PP(s) with C2-I-PP. This is especially true for the version with 200 mb steering predictors for the north-of-ridge category.

Possible reasons for the failure of the speed stratification were examined. Table 5.5 presents the number of cases that occurred for a given height pattern and the subsequent 24-hour cyclone speed. As discussed in Chapter 3, the height patterns for the Atlantic were computed according to:

$$\begin{aligned} H_{15,40} + H_{15,25} - 2 \times H_{15,-5} & \quad \text{for north-of-ridge} \\ H_{10,10} - H_{10,-15} - 20 & \quad \text{for on-the-ridge} \\ 2 \times H_{20,5} - H_{20,-25} - H_{20,25} & \quad \text{for south-of-ridge} \end{aligned}$$

where $H_{i,j}$ is the 500 mb height in meters and the subscripts i and j indicate the degrees of latitude and longitude away from the cyclone center where the heights are to be observed. Latitudes are positive poleward and longitudes are positive eastward from the cyclone center. Recall that if the height pattern indicator HP was greater than or equal to zero, the cyclone was placed in the fast category and if HP was less than zero, the cyclone was placed in the slow category. Although the stratification worked well for the on-the-ridge category, it did poorly for the other two categories. For a given value of the height pattern indicator, there are as many cases that were fast as there were slow. The scheme did a poor job of distinguishing the fast cases from the slow cases for the given height pattern indicator. The results in Table 5.4 bear this out.

Similar speed stratification problems occurred in the NW Pacific as shown in Table 5.6. Although it appears that the height pattern indicator was able to distinguish between the very fast and the very

TABLE 5.5

Number of Atlantic cases that occurred for a given magnitude of 500 mb height pattern indicator (in meters) and subsequent 24-hour cyclone speed (in m/s).

	$S < 2.5$	$2.5 \leq S \leq 7.5$	$S > 7.5$	
<u>North</u>	78	238	144	100 < HP
	15	59	46	50 < HP \leq 100
	12	95	37	0 \leq HP \leq 50
	24	68	33	-50 \leq HP < 0
	22	101	43	-100 \leq HP < -50
	175	408	150	HP < -100
<u>On</u>	4	27	17	100 < HP
	4	51	18	50 < HP \leq 100
	26	132	22	0 \leq HP \leq 50
	39	138	2	-50 \leq HP < 0
	15	48	1	-100 \leq HP < -50
	9	14	0	HP < -100
<u>South</u>	48	242	72	100 < HP
	16	112	21	50 < HP \leq 100
	10	127	41	0 \leq HP \leq 50
	10	84	34	-50 \leq HP < 0
	16	140	14	-100 \leq HP < -50
	74	288	9	HP < -100

slow cases based on strongly positive or strongly negative values of HP, this distinction is not as clear as the value of HP approaches zero.

For example, when the height pattern indicator was greater than 100 for the north-of-ridge category, the scheme was able to correctly select almost all of the extremely fast cases. Only 25 cases that actually were slow cases were improperly selected. Similarly, the scheme performed creditably for the on-the-ridge category when the height pattern indicator was greater than 100 and for the south-of-ridge category when a negative height pattern indicator was used to select the extremely slow cases.

The scheme did poorly, however, on all other occasions. The worst examples are for the on-the-ridge and south-of-ridge categories when the height pattern indicator was between zero and 100. More of the cases

TABLE 5.6

Number of NW Pacific cases that occurred for a given magnitude of 500 mb height pattern indicator (in meters) and subsequent 24-hour cyclone speed in (m/s).

	$S < 2.5$	$2.5 \leq S \leq 7.5$	$S > 7.5$	
<u>North</u>	25	244	347	100 < HP
	27	141	90	50 < HP \leq 100
	52	159	73	0 \leq HP \leq 50
	47	174	45	-50 \leq HP < 0
	119	357	59	-100 \leq HP < -50
	168	453	73	HP < -100
<u>On</u>	17	229	100	100 < HP
	58	388	34	50 < HP \leq 100
	112	504	21	0 \leq HP \leq 50
	27	137	5	-50 \leq HP < 0
	127	374	59	-100 \leq HP < -50
	170	456	74	HP < -100
<u>South</u>	289	1930	449	100 < HP
	194	1027	165	50 < HP \leq 100
	210	971	89	0 \leq HP \leq 50
	157	561	31	-50 \leq HP < 0
	93	271	6	-100 \leq HP < -50
	134	327	9	HP < -100

selected for the fast set actually turned out to be slow cases. Perhaps, the speed stratification could have been made on very large positive or negative values of HP instead of zero as was done in the stratification here. But this would have resulted in a very small sample size. Further, the fast and slow equations could have been applied to only those cyclone cases with initial speeds greater than 7.5 m/s or less than 2.5 m/s, respectively, as was done in a similar manner for NHC-67. Neither approach was pursued here and the decision was made to use the regression equations without any speed stratification. All further reference to CSU84 for the Atlantic will refer to the version without any speed stratification.

Table 5.7 compares the skill of CSU84 to the official forecast error and the operational error of the best objective technique for a nearly homogeneous sample for the period 1973-1979. Direct comparison between the operational and CSU84 errors are difficult since the CSU84 cases during the period are a combination of dependent and independent cases. For this comparison, just the dependent and independent cases for 1973-1979 from the larger 1962-1981 CSU84 runs were used. The on-the-ridge and north-of-ridge categories were combined to form the north zone. This appeared reasonable since most of the on-the-ridge cases were north of 24.5°N .

These results for CSU84 are based on perfect-prog data, best track initial positions and 200 mb steering predictors and appear to indicate that the accuracy of CSU84 is comparable to the best operational technique at the short forecast period and much better at the longer forecast periods. Relative to the other objective techniques currently used by the National Hurricane Center, CSU84 appears far superior. For example, the 72-hour forecast errors for the north zone range from 401 n mi for NHC72 to 499 n mi for NHC67 and for the south zone, the errors range from 309 n mi for HURRAN to 355 n mi for NHC72.

For the purpose of comparison with a no-skill forecast, Table 5.8 presents 24- and 48-hour forecast errors based only on an extrapolation of the cyclone's past motion using the CSU84 1973-1979 dependent and independent sets combined. The Table reveals that the use of past 12-hour motion for persistence is far better than either the past 24-hour motion or the average of the past 12- and past 24-hour motion. But as the results indicate, pure persistence is a poor indicator of future

TABLE 5.7

Comparison of forecast errors (n mi) on a nearly homogeneous sample of cyclone cases for 1973-1979 between CSU84 using 200 mb steering and perfect-prog on dependent (C2-D-PP/(73-79/BT)) and independent (C2-I-PP/(73-79/BT)) data and the official NHC forecast (OFF) and the best track (BEST) operational objective technique. The forecast errors for the official and the best objective techniques for each category are from Neumann and Pelissier (1981). The north-of-ridge and on-the-ridge categories for CSU84 were combined to form the north zone. Number of cases are in parentheses.

	24-HR				48-HR				72-HR			
	C2-D-PP	C2-I-PP	OFF	BEST	C2-D-PP	C2-I-PP	OFF	BEST	C2-D-PP	C2-I-PP	OFF	BEST
<u>North</u> ($>24.5^{\circ}\text{N}$)	107(104)	135(38)	131(156)	127(156) NHC 67	199(89)	242(19)	304(102)	272(102) NHC 73	289(80)	316(10)	421(60)	358(60) NHC 73
<u>South</u> ($<24.5^{\circ}\text{N}$)	82(67)	99(114)	85(129)	88(129) CLIPER	151(64)	159(43)	179(95)	180(95) NHC 73	194(59)	253(34)	317(79)	298(79) CLIPER
All	97(171)	108(152)	110(285)	113(285) NHC 73	179(153)	184(62)	244(197)	228(197) NHC 73	249(139)	267(44)	362(139)	344(139) NHC 73

TABLE 5.8

Track error (n mi) for a forecast using only persistence for all cyclone cases for the period 1973-79. Forecast based on an extrapolation of the cyclone's past 12-hour motion (P_{12}), past 24-hour motion (P_{24}), and an average of the past 12- and past 24-hour motion (P_{12+24}) are shown.

	24-HR			48-HR		
	P_{12}	P_{24}	P_{12+24}	P_{12}	P_{24}	P_{12+24}
North	169(102)	188(102)	176(102)	417(102)	440(102)	424(102)
On	158(40)	184(40)	170(40)	468(40)	514(40)	489(40)
South	88(211)	97(211)	91(211)	216(211)	230(211)	220(211)
All	130(323)	146(323)	136(323)	336(323)	360(323)	345(323)

motion outside the deep tropics. Note that forecast errors at 48 hours are well above 400 n mi for the north- and on-the-ridge categories compared to the 48-hour errors of CSU84 that are about half as large.

In the development of this new tropical cyclone prediction model, the emphasis was on improving the track forecast skill at the higher latitudes for the longer forecast periods. These results appear to indicate that this goal has been achieved. Moreover, the remarkable accuracy of the model at 24 hours was unexpected. On reexamination, there are several reasons for the model's very good performance for both the short- and long-term forecast. These reasons will be amplified later in this chapter.

Operational Simulation. The verification of this new model thus far has used best track data and a perfect-prog approach. In order to simulate more realistic, operational conditions, the sensitivity of the model was evaluated by introducing errors into the initial best track positions. For the seven year period between 1968 and 1974, Neumann (1975) cites an average initial position error of 25 n mi, with the average error decreasing slightly to 22 n mi for cyclones within 500 n mi of the United States (US). With this as a guide and using the model run with 200 mb steering for the data period 1962-81 (C2-D-PP(s)/(62-81/BT)) as the control case, the initial position was perturbed by .3 degrees (18 n mi) for those cyclones west of the 70th meridian and by .5 degrees (30 n mi) for those cyclones east of the 70th meridian.

Since the use of best track information to compute the past 12-hour and 24-hour motion results in perfect persistence predictors, introducing 'erroneous' initial positions can be expected to result in larger forecast errors. However, with the emphasis placed on this model

for more accurate long-range position forecasts, it was hoped that the deterioration of skill due to the initial position error would be reduced at the longer time period. The results of the sensitivity test show that this indeed is the case. Compare the results shown in Table 5.9 with those of C2-D-PP(s) in Table 5.3.

As one might expect, displacing the initial position northward by 18 to 30 n mi degrades primarily the 24-hour forecast position and the degradation decreases with time until it is almost negligible at 72 hours.

The degradation is most noticeable for cyclones south of the ridge (40% increase in error at 24 hours) and is most pronounced for a northward displacement of the initial position compared to displacements southward, eastward or westward. This sensitivity test indicates that the use of best track positions rather than warning positions to produce "perfect" past-motion predictors does not result in an unrealistically strong reliance on the persistence component of the model beyond 24 hours, particularly for those cyclones on and north of the subtropical ridge.

One likely reason for the relatively small increase in error due to initial position error, even for the short-term forecast, is that the model does not use the cyclone's current motion as one of its predictors. Statistical models, such as CLIPER and NHC73 that do use current motion will undoubtedly suffer a large increase in forecast errors at the shorter forecast periods whenever large initial position errors are encountered operationally. Even a relatively small initial position error could be disastrous if the error projects a false change in direction. Use of past 12-hour and past 24-hour motion instead of

TABLE 5.9

Forecast errors (n mi) and percent increase in forecast error (in parentheses) as a result of displacing the best track initial position northward (N), southward (S), westward (W), and eastward (E). Model run C2-D-PP(s)/(62-81/ET) was used as the control case and the initial position was displaced by .3 degrees (18 n mi) if the initial position was west of the 70th meridian and .5 degrees (30 n mi) if the initial position was east of the 70th meridian.

	24-HR				48-HR				72-HR			
	N	S	W	E	N	S	W	E	N	S	W	E
<u>North</u>												
Fast	110(29)	100(18)	87(02)	90(06)	202(14)	197(11)	182(03)	187(06)	353(06)	353(06)	328(-2)	335(0)
Slow	119(04)	113(01)	116(02)	116(02)	181(03)	169(-4)	174(-1)	174(-1)	209(04)	196(-2)	204(02)	200(0)
Total	116(13)	109(06)	105(02)	106(03)	189(07)	179(02)	177(01)	179(02)	266(06)	255(01)	251(0)	253(0)
<u>On</u>												
Fast	91(34)	73(07)	74(09)	83(18)	158(16)	138(01)	140(03)	143(05)	224(10)	203(0)	215(05)	205(0)
Slow	84(27)	74(12)	71(08)	79(20)	154(18)	133(02)	148(13)	133(02)	277(06)	272(05)	284(09)	260(0)
Total	88(31)	74(10)	73(09)	81(21)	156(17)	136(02)	144(08)	139(04)	252(09)	239(03)	250(08)	232(0)
<u>South</u>												
Fast	92(46)	85(35)	79(25)	81(27)	161(25)	144(12)	138(07)	141(06)	255(24)	212(03)	221(07)	224(05)
Slow	81(23)	78(18)	72(09)	77(18)	148(15)	139(08)	137(06)	143(11)	216(06)	218(07)	213(05)	212(01)
Total	87(40)	82(28)	76(19)	79(22)	154(19)	142(10)	138(07)	142(08)	236(15)	215(05)	217(06)	218(03)
<u>All</u>	99(24)	91(04)	87(09)	90(12)	168(13)	155(04)	154(03)	156(04)	251(10)	236(03)	237(03)	235(01)

current motions could be expected to 'soften' the impact of any initial position error.

However, the use of 'real' prognostic data in lieu of analysis data, as was done in this perfect-prog approach, will almost certainly degrade the results; just how much is questionable and must be tested in an operational environment. With more sophisticated numerical models and more accurate prognostic fields, the degradation will hopefully be minimal.

Again, because of the new approach taken here of segmenting future 72-hour cyclone motion into three discrete 24-hour time steps, the dependence of the scheme on any one prognostic field is limited to 24 hours of cyclone movement. Thus, the extent of any erroneous track forecast based on a 'bad' prognostic field should be kept to a minimum and hopefully corrected on a subsequent 24-hour forecast. In addition, because the design of this model permits forecaster intervention in providing the input data, if the analysis or prognostic field appears to be obviously in error, the input data required by the model could be easily modified prior to the computation of the forecast position.

Another desirable feature of this model is that it does not use prognostic data to formulate the 24-hour forecast position. Nor does it use the current motion of the cyclone. The synoptic predictors required for calculating the first 24 hours of motion come from the current and 24-hour old analyses. Further, only the 24-hour prog fields are used for computing the 24- to 48-hour motion and likewise, only the 48-hour prog fields are used to compute the 48- to 72-hour motion. This may explain the sizeable degradation in skill experienced by traditional statistical-dynamical cyclone prediction models that apply 24-, 36-, and

48-hour forecast fields for each and every forecast period in transitioning from a perfect-prog approach used in development to an operational setting that uses real progs.

Figure 5.1, taken from Neumann and Lawrence (1973), is presented as an example of the predictors selected by the NHC73 screening program for zonal and meridional motion for zone 22 which is centered near the eastern tip of Cuba. Their H0010 refers to the current 1000 mb height, H2405 refers to the 24-hour forecast height of the 500 mb surface, H4805 refers to the 48-hour forecast height of the 500 mb surface, and so on. Note that their short range 12- and 24-hour forecasts are heavily dependent on forecast fields. Specifically, 10 of the 12 predictors for 24-hour zonal motion come from forecast fields while 7 of the 12 predictors for 24-hour meridional motion come from forecast fields. And a fair number of these predictors come from the 48-hour forecast field. Since forecast fields for the tropics are known to be rather poor and zone 22 can be considered to lie in the tropics, the use of forecast fields, particularly extended forecasts for 36 and 48 hours, can be expected to play a significant role in the degradation of statistical forecast models when actual forecast fields are used operationally.

Model Runs Using Operational Data. To determine the amount of degradation that might occur in using this newly developed model operationally, the model was tested using actual forecast fields from a numerical model. This was accomplished using prognostic fields archived at the Fleet Numerical Oceanography Center (FNOC) for the period 1968-1981. Twenty-four- and 48-hour forecast fields of sea level pressures and 500 mb D-values on a 63x63 hemispheric grid were used to introduce

Predictor Selection Order	12 HOUR FCST (k=1)			24 HOUR FCST (k=2)			36 HOUR FCST (k=3)			48 HOUR FCST (k=4)			72 HOUR FCST (k=5)		
	Predictor	RV		Predictor	RV		Predictor	RV		Predictor	RV		Predictor	RV	
1	H0005	37	0.626	H2405	37	0.643	H2405	37	0.665	H2405	37	0.659	H2405	37	0.515
2	H0005	52	0.043	H0005	37	0.064	H0010	74	0.052	H0005	88	0.073	H0005	88	0.132
3	H0010	75	0.055	H0010	75	0.042	H0005	37	0.044	H2405	65	0.042	H2405	80	0.047
4	H3605	54	0.033	H2405	22	0.038	H0005	103	0.034	H3605	54	0.040	H0005	46	0.052
5	H2405	50	0.031	H2405	12	0.021	H3605	54	0.020	H3605	56	0.034	H2405	37	0.035
6	H2405	10	0.020	H3605	38	0.023	H2405	41	0.024	H0010	74	0.017	H0005	37	0.030
7	H0005	88	0.014	H3605	65	0.016	H2405	65	0.022	H2405	94	0.017	H3605	54	0.019
8	H0010	52	0.013	H2405	01	0.015	H0007	22	0.022	H3605	01	0.010	H0010	75	0.022
9	H2405	13	0.012	H3605	64	0.011	H3605	01	0.009	H0005	37	0.007	H2405	01	0.015
10	H2405	54	0.012	H2405	85	0.009	H0005	03	0.011	H2405	31	0.011	H3605	03	0.013
11	H2405	80	0.012	H3605	54	0.009	H2405	37	0.007	H2405	77	0.005	H3605	80	0.006
12	H2405	57	0.008	H3605	50	0.009	H2405	77	0.006	H3605	98	0.005	H3605	79	0.011
Total Reduction			0.879			0.900			0.917			0.922			0.897

Predictor Selection Order	12 HOUR FCST (k=1)			24 HOUR FCST (k=2)			36 HOUR FCST (k=3)			48 HOUR FCST (k=4)			72 HOUR FCST (k=5)		
	Predictor	RV		Predictor	RV		Predictor	RV		Predictor	RV		Predictor	RV	
1	H2405	65	0.167	H2405	50	0.183	H2405	50	0.211	H2405	50	0.254	H2405	50	0.237
2	H0005	65	0.145	H2405	80	0.208	H2405	80	0.196	H2405	80	0.175	H2405	47	0.148
3	H0007	84	0.188	H2405	84	0.098	H2405	84	0.073	H0007	61	0.076	H3605	73	0.091
4	H0005	30	0.046	H0005	65	0.058	H0007	61	0.049	H0010	61	0.046	H0005	85	0.042
5	H2405	56	0.038	H0007	61	0.054	H0005	65	0.047	H0005	88	0.047	H0010	80	0.061
6	H2405	50	0.028	H0007	84	0.029	H0005	64	0.026	H0010	80	0.057	H2405	37	0.031
7	H0010	63	0.022	H0005	14	0.026	H2405	37	0.027	H0007	95	0.029	H2405	22	0.030
8	H2405	97	0.019	H0005	94	0.022	H3605	96	0.026	H2405	102	0.025	H2405	37	0.028
9	H2405	13	0.017	H2405	30	0.020	H3605	22	0.023	H0005	19	0.023	H2405	99	0.029
10	H2405	38	0.014	H3605	36	0.021	H2405	30	0.015	H0007	63	0.010	H2405	76	0.025
11	H2405	2	0.018	H3605	96	0.017	H0005	14	0.013	H2405	35	0.009	H0010	58	0.015
12	H0007	30	0.015	H2405	86	0.016	H3605	36	0.011	H3605	21	0.016	H3605	50	0.018
Total Reduction			0.717			0.751			0.747			0.767			0.756

Fig. 5.1. Predictors selected by the NHC73 screening program for zonal and meridional motion for zone 22. H0005 refers to the current 500 mb height, H3605 refers to the 36-hour forecast height of the 500 mb surface, H0007 refers to the current 700 mb height, H0010 refers to the current 1000 mb height and so on. The tables are taken from Neumann and Lawrence (1973).

synoptic data at the appropriate time. A standard height of 5574 m was used to convert the 500 mb D-values to geopotential heights.

Unfortunately, 200 mb prognostic height fields are not archived by the FNOC. Comparative testing is thus limited to the version of the model using 500 mb steering predictors instead of 200 mb steering predictors. Although comparing the independent set results of model run C5-I-PP/(62-81/BT)) and C2-I-PP/(62-81/BT)) in Table 5.4 would indicate that the version with 500 mb steering is not as accurate as the version with 200 mb steering, the verification runs using actual forecast fields should be able to indicate the amount of degradation in forecast accuracy that the model would suffer.

Table 5.10A presents a comparison of the model using perfect-prog data (C5-DI-PP/(68-81/BT)) and actual forecast fields (C5-DI-AP/(68-81/BT)). Verification of the model using both actual forecast fields and perturbation of the initial position (C5-DI-AP/(68-81/PBT)) is also shown. To simulate warning positions, the best track initial positions were randomly perturbed by an amount equal to warning position error as observed operationally (Neumann, 1975). The relatively small amount of degradation resulting from the use of actual forecast fields and pseudo-warning positions is comforting. As expected, the largest increases in error using real progs occur for the south-of-ridge and on-the ridge categories. The poor quality of forecast fields in the tropics is well-known. This is precisely where statistical schemes that do not rely on synoptic data perform well. Yet, the results indicate that the skill of this model compares very favorably with these analog techniques that use just climatology and persistence and, as will be

TABLE 5.10A

Verification of the model for Atlantic using perfect-progs (C5-D-PP/(68-81/BT)); actual progs (C5-D-AP/(68-81/BT)); actual progs and pseudo-warning positions (C5-D-AP/(68-81/PBT)) for the Atlantic for 1968-1981. The model uses 500 mb steering instead of 200 mb steering. Number of cases are in parentheses and they differ beyond 24 hours due to missing forecast fields.

	24-HR			48-HR			72-HR		
	C5-DI-PP 68-81/BT	C5-DI-AP 68-81/BT	C5-DI-AP 68-81/PBT	C5-DI-PP 68-81/BT	C5-DI-AP 68-81/BT	C5-DI-AP 68-81/PBT	C5-DI-PP 68-81/BT	C5-DI-AP 68-81/BT	C5-DI-AP 68-81/PBT
<u>North</u>	106(329)	106(329)	111(329)	207(294)	219(157)	216(157)	297(273)	321(150)	319(150)
<u>On</u>	84(118)	84(118)	91(118)	139(96)	167(96)	164(94)	222(81)	303(87)	294(85)
<u>South</u>	85(397)	85(397)	91(397)	148(330)	172(358)	176(358)	211(296)	259(348)	261(348)
<u>All</u>	93(844)	93(844)	99(844)	171(720)	184(611)	184(609)	248(650)	282(585)	281(583)

TABLE 5.10B

Verification of the model for Atlantic on independent set using perfect progs for 1968-1981.

	24-HR		48-HR		72-HR	
	C5-I-PP 68-81/BT	C5-I-PP 68-81/PBT	C5-I-PP 68-81/BT	C5-I-PP 68-81/PBT	C5-I-PP 68-81/BT	C5-I-PP 68-81/PBT
<u>North</u>	122(94)		242(73)		358(59)	
<u>On</u>	102(53)		160(39)		263(32)	
<u>South</u>	96(228)		166(166)		242(138)	
<u>All</u>	103(375)		185(278)		275(229)	

shown later, outperforms them at the longer forecast periods for the south zone. At higher latitudes, this model appears superior.

The forecast errors for the on-the-ridge category are the key to whether the model is capable of discerning a major track change from one with a westward component to one with an eastward component. Although there appears to be a sizeable degradation in skill by introducing actual forecast fields, bear in mind that model run C5-DI-PP was an attempt to compare homogeneous cyclone cases for the period 1968-1981.

By keeping the sample cases homogeneous, however, both dependent and independent cases from the perfect-prog approach were combined. Table 5.10B shows the results from the model run (C5-I-PP) on just the independent set using perfect-progs for the period 1968-1981. Using these forecast errors for comparison, the degradation from using actual prognostic fields is relatively small. A truly homogeneous sample would probably have resulted in forecast errors somewhere between the two model runs of C5-DI-PP shown in Table 5.10A and model run C5-I-PP shown in Table 5.10B. Be aware that although the 1968-1981 data set is a mixture of dependent and independent data for the perfect-prog case, it can be considered totally independent beyond 24 hours for the actual prog case. From these results, it would appear safe to assume that the use of this model in an operational setting would not degrade its forecast skill as much as the deterioration suffered by the other statistical-dynamical models. Possible explanations why the approach used in the development of CSU84 limits the normal operational degradation suffered by statistical models will be offered in the summary to this chapter.

5.2 NW Pacific and South China Sea

The development of regression equations for the NW Pacific and South China Sea followed along the same line taken for the Atlantic. As was shown in Table 5.6, speed stratification was not beneficial for the Pacific; thus, only the versions of the model with no speed stratification will be discussed from here on. Table 5.11 summarizes the various model runs for the NW Pacific for easy reference. Table 5.12 presents verification results for the dependent and independent sets using either the 500 mb steering predictors or 200 mb steering predictors. Unlike the Atlantic where the version of the model using 200 mb steering was more accurate overall, the version with 500 mb steering was more accurate overall in the NW Pacific, except for intense cyclones which are accelerating north of the subtropical ridge. The reason for this is unclear although a likely explanation is the difference in the percent of cases in the north-of-ridge category compared to the cases in the south-of-ridge category for the two ocean basins. As will be shown later, even for the NW Pacific, the version using 200 mb steering was more accurate for those strong cyclone cases undergoing recurvature north of the ridge. But since the number of these cases is small compared to the other cases for the Pacific, the accuracy of the version with 500 mb steering appears better overall.

The model's better performance on strong cyclones undergoing recurvature when 200 mb steering is used instead of 500 mb steering appears to support recent findings correlating the recurvature phenomenon with upper tropospheric winds. A number of these studies were received earlier in Chapter 2.

TABLE 5.11

List of the various model runs for the NW Pacific. Note that the symbolic name for each run denotes the level of the steering predictors, dependent or independent set, perfect-prog or actual prog, speed stratification, data period, and best track initial position or perturbed best track initial position to simulate a pseudo-warning position.

CSU84 Model	Steering Level	Dependent (D) or Independent (I)	Perfect-Prog(PP) Actual Prog (AP) No Prog (NP)	Speed Stratification	Data Period	Initial Position
C5-D-PP 62-81/BT	500 mb	D	PP	NO	1962-81	Best Track (BT)
C5-I-PP 62-81/BT	500 mb	I	PP	NO	1962-81	BT
C2-D-PP 62-81/BT	200 mb	D	PP	NO	1962-81	BT
C2-I-PP 62-81/BT	200 mb	I	PP	NO	1962-81	BT
C5-D-PP 79-81/BT	500 mb	D	PP	NO	1979-81	BT
C5-I-PP 79-81/BT	500 mb	I	PP	NO	1979-81	BT
C5-I-PP 62-81/PBT	500 mb	I	PP	NO	1962-81	Perturbed BT(PBT)
C5-DI-PP 68-81/BT	500 mb	D+I	PP	NO	1968-81	BT
C5-DI-AP 68-81/BT	500 mb	D+I	AP	NO	1968-81	BT

TABLE 5.11 (cont'd)

CSU84 Model Runs	Steering Level	Dependent (D) or Independent (I)	Perfect-Prog (PP) Actual Prog (AP) No Prog (NP)	Speed Stratification	Data Period	Initial Position
C5-DI-AP 68-81/PBT	500 mb	D+I	AP	NO	1968-81	PBT
C5-I-PP 68-81/BT	500 mb	I	PP	NO	1968-81	BT
C5-DI-AP 79-81/PBT	500 mb	D+I	AP	NO	1979-81	PBT

TABLE 5.12

Comparison of forecast errors (n mi) between model runs using 500 mb steering on dependent (C5-D-PP) and independent (C5-I-PP) data and 200 mb steering on dependent (C2-D-PP) and independent (C2-I-PP) data for the NW Pacific for 1962-81. Number of cases are in parentheses.

	NW PACIFIC				72-HR			
	24-HR		48-HR		48-HR		72-HR	
	C5-D-PP	C5-I-PP	C2-D-PP	C2-I-PP	C5-D-PP	C5-I-PP	C2-D-PP	C2-I-PP
North	77(122)	95(75)	73(120)	111(75)	135(89)	171(57)	134(88)	205(57)
On	60(256)	81(131)	59(240)	82(127)	121(215)	161(105)	118(196)	171(102)
South	76(1322)	80(667)	76(1322)	81(667)	144(1243)	155(617)	144(1236)	159(615)
All	74(1700)	81(873)	74(1682)	84(869)	141(1547)	157(779)	140(1520)	164(774)
					197(1410)	221(703)	199(1381)	231(697)

TABLE 5.12 (cont'd)

SOUTH CHINA SEA

Comparison of forecast errors (n mi) for South China Sea (SCS) cyclones using the regression equations developed on SCS cyclones (dependent) and using the regression equations developed on NW Pacific cyclones (independent).

	<u>24-HR</u>	<u>48-HR</u>	<u>72-HR</u>
<u>ALL</u> (Dependent)	74(395)	146(376)	223(361)
<u>North</u> (Independent) 83(47)		181(43)	275(40)
<u>On</u> (Independent) 68(35)		108(32)	195(31)
<u>South</u> (Independent) 68(359)		138(337)	210(321)
<u>ALL</u> (Independent) 70(441)		140(412)	215(392)

In the Atlantic, however, the percent of cases in the north-of-ridge category is rather high compared to the number of cases in the other categories. Thus, the skill of the model with 200 mb steering for the north-of-ridge category translates to better skill overall.

Table 5.12 also shows the verification results for the South China Sea. The verification for the dependent set uses the regression equations that were developed using the surface pressure, 850 mb heights, 700 mb heights, and 500 mb heights with no ridge or speed stratification. The independent set is comprised of the same cyclone cases but uses the regression equations developed for the NW Pacific cyclones. Note that comparable results are obtained using the NW Pacific regression equations. Thus, unless it is impossible to select the proper ridge category, it is suggested that the regression equations developed for the NW Pacific be used for the South China Sea.

Table 5.13 presents a comparison between the CSU84 version with 500 mb steering and perfect-prog data and the official forecast and the best objective technique for the period 1979-1981. These operational errors were compiled from the Annual Tropical Cyclone Report (1979-1981). Over the last few years, the best objective technique has been the One-Way Interactive Tropical Cyclone Model (OTCM). Although one of the objectives in the development of a new prediction model was the improvement at the longer forecast periods, sizeable reduction in forecast error is also evident at the shorter period.

Analogous to the Atlantic, the sensitivity of the model was evaluated by perturbing the initial cyclone position as a way of simulating operational conditions. Using the mean deviation of satellite-derived cyclone positions from the JTWC best track positions

TABLE 5.13

Forecast errors (n mi) of CSU84 using 500 mb steering and perfect-prog data on dependent (CS-D-PP) and independent (CS-I-PP) sets for the NW Pacific compared to the official (JTWC) forecast errors and the operational errors of the best objective technique (OTCM). The comparison is based on a nearly homogeneous sample of cyclone cases for the years 1979-1981. The forecast errors for the official (JTWC) and the best operational technique (OTCM) were compiled from the Annual Typhoon/Tropical Cyclone Reports (1979-1981). The number of cases appear in parentheses.

	24-HR			48-HR			72-HR		
	<u>CS-D-PP</u>	<u>CS-I-PP</u>	<u>JTWC</u>	<u>CS-D-PP</u>	<u>CS-I-PP</u>	<u>JTWC</u>	<u>CS-D-PP</u>	<u>CS-I-PP</u>	<u>JTWC</u>
<u>North</u>	77(122)	95(75)	---	135(89)	171(57)	---	188(71)	242(42)	---
<u>On</u>	60(256)	81(131)	---	121(215)	161(105)	---	199(172)	252(91)	---
<u>South</u>	76(1322)	80(667)	---	144(1243)	155(617)	---	198(1167)	215(570)	---
<u>ALL</u>	74(1700)	81(873)	121(2570)	141(1547)	157(779)	237(1984)	197(1410)	221(703)	357(1499)
			122(1204)			185(969)			345(727)

for 1974-1983 (calculated from figures in Table 2-3 of the 1983 Annual Tropical Cyclone Report of 13.3 n mi for cyclones possessing a well-defined eye, 19.3 n mi for cyclones possessing a well-defined circulation center and 35.8 n mi for all others), the following adjustments to the initial best track positions were made:

- 1) if the intensity of the cyclone was greater than 69 kts, the initial position was altered by .2 degrees (12 n mi);
- 2) if the intensity of the cyclone was between 35 and 69 kts, the initial position was altered by .3 degrees (18 n mi);
- 3) otherwise, the initial position was altered by .5 degrees (30 n mi);

Based on the sensitivity test done on the Atlantic cases indicating that initial position errors increase the forecast errors the most when the estimated initial position is in error to the north of the actual position, all of the best track initial latitudes were increased northward by the adjustments cited above. Model run C5-I-PP/(62-81/BT) using 500 mb steering on the 1962-1981 independent set was used as the control run. The results shown in Table 5.14 are, therefore, for the worst case situation. In addition, since cyclone intensities were not recorded on every forecast situation prior to 1977, and since these cases appear with an intensity of zero in the best track file, the initial positions were altered by an amount greater than necessary on many of the cases. Also, with the 1983 typhoon season, JTWC no longer extrapolates forward 2-3 hours to estimate a warning position. Instead, the reconnaissance fix is made at the synoptic time of the warning and no extrapolation of the initial warning position is necessary. Thus,

TABLE 5.14

Forecast errors (n mi) in the NW Pacific and the percent increase in error as a result of displacing the best track initial position northward (PBT) either 12, 18 or 30 n mi depending on cyclone intensity. Model run C5-I-PP/(62-81/BT) was used as the control case and appears as BT in the table.

	24-HR			48-HR			72-HR		
	BT	PBT	%	BT	PBT	%	BT	PBT	%
<u>North</u>	95(75)	113(75)	19%	171(57)	192(57)	12%	242(42)	269(42)	11%
<u>On</u>	81(131)	97(131)	20%	161(105)	185(105)	15%	252(91)	279(91)	11%
<u>South</u>	80(667)	95(667)	19%	155(617)	167(617)	8%	215(570)	224(570)	4%
<u>All</u>	81(873)	97(873)	20%	157(779)	171(779)	9%	221(703)	234(703)	6%

initial position error now can be expected to be reduced somewhat from those prior to 1983.

As with the Atlantic sensitivity test, Table 5.14 indicates that the impact of a poor initial position is greatest at 24 hours and decreases steadily to about an 11% increase in error at the higher latitude at 72 hours. Unlike the Atlantic, however, the effect of displacing the initial position northward was smallest south of the ridge.

Model Runs Using Operational Data. The model was tested on NW Pacific cyclones using actual forecast fields produced by the Fleet Numerical Oceanography Center (FNOC) hemispheric primitive equation model. Again, because 200 mb prognostic heights are not archived, the version of the model with 500 mb steering was used. For the NW Pacific, this presented no problems since this version was more accurate overall than the version of the model with 200 mb steering. Table 5.15A

TABLE 5.15A

Verification of the model for 1968-1981 using perfect-progs with both dependent and independent sets (C5-DI-PP/(68-81)/BT); actual progs (C5-DI-AP/(68-81)/BT); actual progs and pseudo-warning positions (C5-DI-AP/(68-81)/PBT) for the NW Pacific. The model uses 500 mb steering. Number of cases are in parentheses and they differ beyond 24 hours due to missing forecast fields.

	24-HR			48-HR			72-HR		
	C5-DI-PP 68-81/BT	C5-DI-AP 68-81/BT	C5-DI-AP 68-81/PBT	C5-DI-PP 68-81/BT	C5-DI-AP 68-81/BT	C5-DI-AP 68-81/PBT	C5-DI-PP 68-81/BT	C5-DI-AP 68-81/BT	C5-DI-AP 68-81/PBT
<u>North</u>	80(104)	80(104)	88(104)	141(74)	150(51)	153(51)	190(58)	265(41)	274(41)
<u>On</u>	69(291)	69(291)	76(291)	132(238)	136(219)	142(219)	216(195)	256(187)	260(187)
<u>South</u>	78(1509)	78(1509)	85(1509)	149(1403)	163(1380)	168(1380)	204(1310)	251(1339)	256(1339)
<u>All</u>	77(1904)	77(1904)	84(1904)	146(1715)	159(1650)	164(1650)	205(1563)	252(1567)	257(1567)

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TABLE 5.15B

Verification of the model on independent set using perfect-progs for 1968-1981.

	24-HR		48-HR		72-HR	
	C5-I-PP 68-81/BT	C5-I-PP 68-81/BT	C5-I-PP 68-81/BT	C5-I-PP 68-81/BT	C5-I-PP 68-81/BT	C5-I-PP 68-81/BT
<u>North</u>	96(46)	96(46)	164(36)	164(36)	214(29)	214(29)
<u>On</u>	83(100)	83(100)	160(81)	160(81)	253(71)	253(71)
<u>South</u>	81(527)	81(527)	157(490)	157(490)	219(453)	219(453)
<u>All</u>	82(673)	82(673)	158(607)	158(607)	223(553)	223(553)

presents the verification of the model using actual forecast fields and pseudo-warning positions (C5-DI-AP/(68-81/PBT)) along with the perfect-prog version (C5-DI-PP/(68-81/BT)) and the actual prog version using best track initial positions (C5-DI-AP/(68-81/BT)). To simulate warning positions, pseudo-warning positions were computed by randomly perturbing the best track initial cyclone positions by an amount equal to warning position errors encountered operationally. Thus, if the cyclone intensity was greater than 69 kts, the initial position was perturbed by 0.2 degrees (12 n mi), for intensities of 35 kts to 69 kts, the initial position was perturbed by 0.3 degrees (18 n mi), for intensities less than 35 kts, the initial position was perturbed by 0.5 degrees (30 n mi).

As in the Atlantic simulation, model run C5-DI-PP was an attempt to compare homogeneous cyclone cases for the period 1968-1981 and as a result, both dependent and independent cases from the perfect-prog approach were combined. Table 5.15B presents the forecast errors using just the independent cases for this time period. A fair comparison between the perfect-prog and real prog verification should lie somewhere between the two runs. Based on this comparison, the increase in forecast error using actual forecast fields ranges from approximately 37% at 72 hours for the north-of-ridge category to approximately 13% at 72 hours for the on-the-ridge category.

A homogeneous comparison of selected techniques for 1979-1981 accomplished by T. Tsui (personal communication) is shown in Table 5.16. For comparison, the forecast errors for CSU84 for the same years with actual forecast fields and with the best track initial positions

TABLE 5.16

A nearly homogeneous comparison of forecast errors (n mi) between CSU84 using 500 mb steering with actual forecast fields and perturbed initial position (C5-DI-AP) and selected dynamical and climatological operational objective techniques for 1979-81 in the NW Pacific (provided by Tsui, NEPRF). In each case, the corresponding official forecast error is indicated in parentheses for a homogeneous sample. HPAC - half persistence and climatology; CLMW - climatology based on warming position; OTCM - one-way interactive dynamical model; NTCM - nested two-way interactive dynamical model.

	<u>24h</u>	<u>48h</u>	<u>72h</u>
OTCM	126(124)	229(233)	320(348)
HPAC	137(126)	231(229)	320(339)
CLMW	157(126)	247(229)	327(343)
NTCM	143(124)	248(235)	354(368)
C5-DI-AP	80(129)	152(235)	235(330)

randomly perturbed (C5-DI-AP/(79-81/PBT)) are also included. Note the very substantial reduction in the forecast error.

Since the largest forecast errors are normally associated with recurving cyclones, an in-depth analysis of the forecast errors for all recurving cyclones during the period 1978-1981 was accomplished. Table 5.17 and Table 5.18 list all of the cyclones that comprise this set along with their respective official forecast errors. Note that with the exception of 1981, the average error for recurving cyclones was significantly greater at 72 hours than the average error for non-recurving cyclones.

The skill of any objective technique and the confidence a forecaster places on a particular technique is based on its ability to forecast a change in the track, either in direction or speed. As mentioned earlier, any simple technique based on persistence and climatology performs satisfactorily on straight-line climatological tracks. Unfortunately, these objective aids do poorly on cyclones that

deviate from their previous course or from climatology. Thus, most objective techniques are least useful in those particular situations when the forecaster needs objective guidance the most.

To evaluate how the new model performed on those difficult cases when the forecaster really needed to rely on objective guidance, the 00Z and 12Z forecast situations that resulted in abnormally high forecast errors (greater than 500 n mi. at 72 hours) were selected from the 1978-1981 set of recurving cyclones presented in Tables 5.17 and 5.18. These forecast situations, along with their subsequent forecast verification are presented in Tables 5.19 through 5.22. The tables also include a homogeneous comparison of all forecasts made for each cyclone. In comparing the official forecast errors and this model's forecast errors, several points should be kept in mind. The official forecast is highly subjective and is strongly affected by political considerations and heavily biased towards the previous forecasts. In contrast, all prediction models, including this model, are objective techniques with little continuity from one forecast to the next. In these respects, the official forecast tends to lag the objective techniques when a large change in direction becomes necessary and thus is at a disadvantage whenever forecast errors are compared. In addition, prior to the 1983 tropical cyclone season, the initial warning position was extrapolated forward approximately three hours from the latest reconnaissance fix

TABLE 5.17

List of official forecast errors for NW Pacific recurving cyclones for 1978 and 1979. Number of forecasts are in parentheses. TY indicates typhoon; TS indicates tropical storm.

<u>1978</u>	<u>24-HR Error</u>	<u>48-HR Error</u>	<u>72-HR Error</u>
#1 TS Nadine	185(16)	568(12)	980(08)
#2 TY Olive	100(32)	224(28)	328(20)
#3 TS Polly	93(12)	139(08)	208(02)
#7 TY Virginia	112(39)	231(35)	399(31)
#15 TY Faye	158(40)	360(36)	514(29)
#18 TY Irma	92(12)	134(08)	154(04)
#19 TY Judy	127(14)	242(10)	346(06)
#22 TY Mamie	182(14)	386(10)	722(06)
#24 TY Ora	124(17)	314(11)	460(05)
#27 TY Phyllis	132(24)	263(20)	436(15)
#29 TS Tess	108(16)	194(12)	367(08)
#31 TY Viola	96(25)	269(21)	434(17)
#32 TS Winnie	<u>238(08)</u>	<u>614(04)</u>	<u>-----</u>
Avg. for recurvers	129(269)	287(215)	451(151)
Avg. for non-recurvers	125(305)	255(220)	370(153)
 <u>1979</u>			
#2 TY Bess	114(17)	265(13)	348(09)
#3 TY Cecil	87(37)	191(33)	320(29)
#4 TS Dot	130(23)	244(20)	315(16)
#12 TY Irving	163(34)	286(30)	441(28)
#13 TY Judy	105(36)	173(27)	277(23)
#15 TS Ken	116(10)	278(07)	415(03)
#16 TY Lola	88(21)	172(19)	287(14)
#19 TY Owen	146(33)	250(29)	327(25)
#21 TS Roger	195(13)	251(09)	303(04)
#23 TY Tip	135(56)	259(52)	345(48)
#27 TY Abby	<u>164(48)</u>	<u>286(39)</u>	<u>338(26)</u>
Avg. for recurvers	132(328)	242(278)	338(223)
Avg. for non-recurvers	114(263)	203(193)	282(145)

TABLE 5.18

List of official forecast errors for NW Pacific recurving cyclones for 1980 and 1981. Number of forecasts are in parentheses. TY indicates typhoon; TS indicates tropical storm.

<u>1980</u>	<u>24-HR Error</u>	<u>48-HR Error</u>	<u>72-HR Error</u>
#2 TS Carmen	154(09)	266(07)	250(05)
#3 TY Dom	137(39)	191(27)	324(23)
#4 TY Ellen	130(31)	300(27)	484(23)
#12 TY Lex	137(32)	314(24)	499(20)
#13 TY Marge	114(26)	276(20)	506(12)
#17 TY Orchid	95(16)	175(12)	284(08)
#20 TY Sperry	176(19)	324(10)	571(08)
#21 TS Thelma	145(11)	358(07)	978(04)
#22 TY Vernon	145(21)	216(17)	248(13)
#23 TY Wynne	119(41)	248(36)	370(30)
#25 TY Betty	131(36)	306(29)	524(28)
#27 TY Dinah	<u>145(13)</u>	<u>304(09)</u>	<u>673(05)</u>
Avg. for recurvers	133(294)	268(225)	442(179)
Avg. for non-recurvers	116(188)	205(139)	283(87)
<u>1981</u>			
#1 TY Freda	106(19)	222(14)	369(09)
#2 TS Gerald	161(15)	289(11)	426(07)
#5 TY June	119(18)	227(13)	196(05)
#18 TY Agnes	104(21)	167(17)	244(12)
#21 TY Doyle	149(10)	269(06)	494(02)
#22 TY Elsie	97(27)	213(23)	377(19)
#24 TY Gay	163(32)	275(27)	410(24)
#25 TY Hazen	130(33)	263(30)	361(26)
#26 TY Irma	<u>76(29)</u>	<u>118(25)</u>	<u>141(21)</u>
Avg. for recurvers	120(204)	222(166)	324(125)
Avg. for non-recurvers	122(254)	216(177)	342(122)

TABLE 5.19

Difficult forecast situations that resulted in 72-hour official forecast errors greater than 500 n mi. A homogeneous comparison for each cyclone is made. The number in parentheses is the number of homogeneous forecast situations. JTWC is the official forecast; C5-I-PP is the model version using 500 mb steering with perfect progs; C2-I-PP is the model version using 200 mb steering with perfect-prog; C5-I-AP is the model version using 500 mb steering with actual prognostic fields and perturbation of the initial position. At 24 hours, results for C5-I-AP are identical to results for C5-I-PP.

1978	24-HR			48-HR			72-HR			
	JTWC	C5-I-PP	C2-I-PP	JTWC	C5-I-PP	C2-I-PP	JTWC	C5-I-PP	C2-I-PP	C5-I-AP
1 TS Nadine	130(4)	74(2)	48(2)	414(4)	121(2)	92(2)	672(2)	89(2)	241(2)	459(2)
010812	19	77	54	186	104	104	564	100	242	348
010900	21	71	42	280	137	80	779	77	239	569
2 TY Olive	43(4)	46(4)	54(4)	84(4)	92(4)	123(4)	75(4)	95(4)	157(4)	91(4)
3 TS Polly	116(2)	72(2)	57(2)	205(2)	157(2)	153(2)	378(1)	176(1)	181(1)	341(1)
7 TY Virginia	108(14)	61(14)	70(14)	222(14)	127(14)	154(14)	398(14)	164(14)	208(14)	221(14)
073000	121	99	125	284	167	187	699	63	20	240
073012	151	75	25	389	127	138	842	174	274	146
15 Faye	177(11)	140(11)	135(11)	428(9)	311(9)	308(9)	587(7)	458(7)	467(7)	537(7)
082900	181	149	136	522	409	376	754	491	414	672
082912	248	211	201	546	399	381	682	403	363	587
083012	196	145	137	511	219	252	719	203	348	134
22 Mamie	117(3)	173(3)	163(3)	270(3)	198(3)	227(3)	714(3)	210(3)	227(3)	435(3)
093012	229	163	125	413	300	262	758	200	113	394
100100	117	229	247	162	214	299	661	144	236	478
100112	5	126	116	234	80	119	722	285	331	434

TABLE 5.19 (cont'd)

1978	24-HR			48-HR			72-HR				
	JTWC	C5-I-PP	C2-I-PP	JTWC	C5-I-PP	C2-I-PP	C5-I-AP	JTWC	C5-I-PP	C2-I-PP	C5-I-AP
24 TY Ora	98(4)	107(4)	100(4)	255(4)	144(4)	122(4)	140(4)	497(3)	178(3)	162(3)	206(3)
101000	115	102	100	347	138	140	117	591	87	70	184
101012	126	110	97	394	146	114	192	507	239	187	260
27 TY Phyllis	100(8)	39(8)	45(8)	261(8)	64(8)	84(8)	109(8)	448(8)	96(8)	118(8)	193(8)
101712	119	28	41	365	45	64	18	569	69	93	118
101800	181	26	52	412	69	67	133	637	92	93	276
101812	98	79	78	327	130	152	200	554	271	252	175
29 TS Tess	191(1)	72(1)	75(1)	397(1)	163(1)	102(1)	94(1)	638(1)	258(1)	266(1)	242(1)
31 TY Viola	69(8)	57(8)	66(8)	207(8)	127(8)	114(8)	141(8)	426(8)	170(8)	179(8)	259(8)
111912	150	73	74	334	122	146	124	500	245	252	309
112000	135	38	58	266	123	131	119	603	199	187	315
112012	11	7	35	155	201	80	192	526	172	149	255
112100	30	103	104	242	176	132	216	741	190	250	335
TOTAL	113(59)	79(59)	80(59)	269(57)	147(57)	154(57)	165(57)	450(51)	192(51)	221(51)	280(51)

TABLE 5.20

Same as Table 5.19 but for 1979.

1979	24-HR			48-HR			72-HR				
	JTWC	C5-D-PP	C2-D-PP	JTWC	C5-D-PP	C2-D-PP	C5-I-AP	JTWC	C5-D-PP	C2-D-PP	C5-I-AP
2 TY Bess	95(5)	59(5)	71(5)	196(5)	135(5)	125(5)	199(5)	392(5)	267(5)	178(5)	384(5)
032012	128	88	80	309	201	208	226	664	367	329	481
032100	109	46	40	250	57	13	271	592	164	28	392
3 TY Cecil	60(13)	41(13)	57(13)	140(13)	68(13)	88(13)	81(10)	252(13)	93(13)	107(13)	119(10)
041512	33	49	110	257	151	143	163	536	233	191	212
041700	138	10	69	339	18	125	---	514	67	245	---
4 TS Dot	94(2)	41(2)	47(2)	134(2)	107(2)	114(2)	89(2)	183(2)	176(2)	215(2)	186(2)
12 TY Irving	145(13)	90(13)	83(13)	267(12)	138(12)	134(12)	138(12)	430(10)	172(10)	161(10)	175(10)
081100	187	194	129	365	277	197	275	572	248	212	329
081112	88	73	65	341	123	124	175	521	134	142	189
081200	103	66	56	321	32	55	41	535	49	42	97
13 TY Judy	89(14)	74(14)	64(14)	166(13)	164(13)	149(13)	160(13)	281(11)	258(11)	223(11)	273(11)
082000	89	63	62	329	210	196	166	649	309	285	255
082012	139	81	67	340	260	234	208	616	268	217	180
15 TS Ken	143(2)	53(2)	43(2)	241(2)	129(2)	132(2)	193(2)	562(1)	290(1)	426(1)	750(1)
16 TY Lola	88(5)	53(5)	48(5)	179(3)	96(3)	97(3)	146(3)	195(1)	74(1)	160(1)	305(1)
19 TY Owen	133(7)	91(7)	84(7)	233(6)	182(6)	190(6)	228(6)	290(5)	254(5)	321(5)	236(5)
092312	309	170	153	445	260	236	264	506	246	228	232

TABLE 5.20 (cont'd)

1979	<u>24-HR</u>		<u>48-HR</u>		<u>72-HR</u>	
	<u>JTWC</u>	<u>C5-D-PP</u>	<u>C5-D-PP</u>	<u>C2-D-PP</u>	<u>JTWC</u>	<u>C5-D-PP</u>
21 TS Roger 100400	268(2) 365	175(2) 248	201(2) 277	329(2) 387	350(2) 586	429(2) 482
23 TY Tip	107(24)	100(24)	98(24)	176(23)	281(22)	203(22)
27 TY Abbey 121000 121012	183(19) 129 108	90(19) 123 72	91(17) 127 51	138(17) 128 96	371(9) 999 1145	151(9) 272 88
TOTAL	121(106)	81(106)	81(104)	145(98)	314(81)	195(81)
				147(96)	191(81)	220(81)
				182(23)	220(22)	220(22)
				152(17)	152(9)	152(9)
				186	403	403
				119	142	142
				162(95)	220(81)	220(81)

TABLE 5.21

Same as Table 5.19 but for 1980.

1980	24-HR			48-HR			72-HR				
	JTWC	C5-D-PP	C2-D-PP	JTWC	C5-D-PP	C2-D-PP	C5-I-AP	JTWC	C5-D-PP	C2-D-PP	C5-I-AP
2 TS Carmen	125(3)	109(3)	112(3)	105(2)	148(2)	133(2)	81(2)	187(3)	133(3)	190(2)	77(2)
3 TY Dom	86(13)	63(13)	60(13)	175(10)	129(10)	123(10)	170(10)	324(8)	171(8)	185(8)	280(8)
4 TY Ellen	111(9)	69(9)	69(9)	278(7)	137(7)	124(7)	118(7)	502(5)	175(5)	143(5)	119(5)
051312	202	70	73	398	128	147	148	574	153	136	212
051412	154	52	89	314	87	89	72	538	155	92	125
5 TY Forrest	117(4)	83(4)	86(4)	198(3)	177(3)	163(3)	181(3)	309(3)	243(3)	236(3)	310(3)
12 TY Lex	145(12)	79(12)	82(12)	326(3)	122(3)	163(3)	138(3)	650(2)	146(2)	207(2)	229(2)
080212	220	36	64	444	127	179	150	775	215	263	265
080300	160	48	76	338	76	134	117	524	77	150	192
17 TY Orchid	89(3)	103(3)	94(3)	133(3)	186(3)	164(3)	191(3)	202(2)	139(2)	155(2)	328(2)
20 TY Sperry	160(5)	68(5)	59(5)	279(3)	164(3)	145(2)	232(3)	500(2)	245(2)	214(2)	382(2)
091600	116	102	90	384	221	215	240	653	270	221	385
21 TS Thelma	193(1)	89(1)	86(1)	490(1)	95(1)	115(1)	320(1)	850(1)	120(1)	152(1)	644(1)
22 TY Vernon	116(5)	69(5)	47(5)	169(5)	123(5)	93(5)	104(5)	180(5)	177(5)	163(5)	255(5)

TABLE 5.21 (cont'd)

1980	24-HR			48-HR			72-HR				
	JTWC	C5-D-PP	C2-D-PP	JTWC	C5-D-PP	C2-D-PP	C5-I-AP	JTWC	C5-D-PP	C2-D-PP	C5-I-AP
23 TY Wynne	108(17)	62(17)	63(17)	230(17)	129(17)	132(17)	141(17)	366(15)	189(15)	190(15)	217(5)
100600	177	105	115	380	224	236	164	510	240	239	211
100700	142	96	75	289	104	57	149	618	84	10	182
100712	119	31	16	305	45	53	39	711	86	116	55
100800	190	47	60	395	91	118	74	692	135	165	89
100812	59	10	26	276	62	83	53	554	79	114	102
100900	104	18	38	332	74	83	60	679	110	119	161
25 TY Betty	139(13)	76(13)	79(13)	304(13)	139(13)	142(13)	141(13)	549(13)	175(13)	182(13)	185(13)
102912	130	241	249	401	499	517	516	554	630	662	645
103100	79	36	50	222	66	67	91	558	140	156	182
103112	181	24	35	431	54	55	36	902	120	141	116
110100	100	18	15	344	80	84	95	527	67	95	77
110112	192	62	62	388	131	148	123	780	61	100	65
110200	221	77	78	438	62	59	118	1056	101	53	166
110212	146	41	49	223	71	31	55	504	145	113	175
110400	54	19	11	260	76	68	80	560	123	167	150
110412	141	62	67	447	38	89	116	918	118	148	192
TOTAL	120(89)	72(89)	68(89)	235(69)	136(69)	129(68)	145(69)	397(60)	177(60)	180(59)	223(60)

TABLE 5.22

Same as Table 5.19 but for 1981.

	<u>24-HR</u>			<u>48-HR</u>			<u>72-HR</u>			
	<u>JTWC</u>	<u>C5-I-PP</u>	<u>C2-I-PP</u>	<u>JTWC</u>	<u>C5-I-PP</u>	<u>C2-I-PP</u>	<u>JTWC</u>	<u>C5-I-PP</u>	<u>C2-I-PP</u>	<u>C5-I-AP</u>
1981										
1 TY Freda	113(4)	81(4)	101(3)	252(3)	184(3)	195(2)	461(2)	290(2)	319(2)	445(2)
2 TS Gerald 041612	235(3) 213	121(3) 198	117(3) 197	394(3) 478	166(3) 297	192(3) 332	451(3) 532	191(3) 283	207(3) 355	258(3) 312
5 TY June	130(3)	50(3)	56(3)	255(3)	107(3)	97(3)	182(1)	148(1)	155(1)	173(1)
18 TY Agnes 082992	65(6) 44	42(6) 60	29(6) 34	112(6) 91	63(6) 27	42(6) 44	256(6) 529	70(6) 53	80(6) 164	151(6) 123
21 Doyle	58(1)	82(1)	---	299(1)	57(1)	---	390(1)	294(1)	---	458(1)
22 TY Elsie 092612	79(8) 225	74(8) 94	66(5) 92	173(7) 421	117(7) 49	89(5) 60	352(6) 531	143(6) 88	112(4) 63	185(6) 178
24 TY Gay 101512 102000	141(11) 374 99	68(11) 73 41	62(11) 66 24	231(11) 535 274	123(11) 133 130	100(11) 114 31	391(11) 929 650	191(11) 110 532	119(11) 67 240	266(11) 189 747
25 TY Hazen 111400 111500	128(8) 156 249	62(8) 23 95	69(8) 42 100	262(8) 467 453	160(8) 146 181	179(8) 205 206	377(8) 852 592	266(8) 262 268	286(8) 371 311	235(8) 221 200
26 TY Irma	39(10)	88(10)	76(10)	103(10)	196(10)	182(10)	128(9)	280(9)	288(10)	249(9)
TOTAL	104(53)	72(53)	65(51)	201(51)	140(51)	131(48)	317(46)	204(46)	196(45)	245(46)
TOTAL (1978-1981)	116(307)	76(307)	74(303)	231(275)	142(275)	141(269)	365(238)	192(238)	196(236)	238(238)

position. As a result, the ensuing initial position error could be expected to have an impact on the subsequent forecast positions.

However, as discussed earlier, sensitivity tests on the model reveal that initial position errors affect the short-term forecast positions as one might expect and the effect becomes almost negligible at the longer forecast periods.

Note that with the exception of TS Roger in 1979 and one forecast for TY Betty in 1980, both versions of CSU84 using perfect-progs and 500 mb steering/200 mb steering consistently produced forecast errors that were much lower than those of the official forecasts. Although the forecast errors for C5-I-AP (that simulates operational conditions) were usually greater than the perfect-prog versions, the errors were consistently less than the official forecast errors. These results appear to indicate that this new prediction model is able to accurately predict cyclone motion even during very difficult situations that resulted in official forecast "busts".

The only instances where the model did poorly (but still much better than the official forecasts) were on TY Faye in 1978 and on the last few forecasts for TY Gay in 1981. Based on the total forecast errors for the period 1978-1981, CSU84 - using actual forecast fields and pseudo-warning positions - was able to decrease the forecast error of this homogeneous sample by more than 30% for all three forecast periods.

5.3 North Indian Ocean

The verification results for the North Indian Ocean with the perfect-prog method are presented in Table 5.23. Although

TABLE 5.23

Verification results for the dependent (C5-D-PP) and independent (C5-I-PP) sets for the North Indian Ocean for 1946-1981 using 500 mb steering and perfect-prog and the official (JWC) and operational error of the best objective technique (BEST) for 1979-1983.

	24-HR				48-HR				72-HR			
	C5-D-PP	C5-I-PP	JWC	BEST	C5-D-PP	C5-I-PP	JWC	BEST	C5-D-PP	C5-I-PP	JWC	BEST
<u>North</u>	62(52)	99(33)	---	---	115(50)	166(20)	---	---	160(47)	237(18)	---	---
<u>On</u>	43(48)	75(21)	---	---	96(48)	144(18)	---	---	158(48)	223(17)	---	---
<u>South</u>	68(527)	72(182)	---	---	123(506)	145(168)	---	---	165(491)	214(161)	---	---
ALL	66(627)	76(236)	135(146)	131(137)	121(604)	147(206)	265(77)	258(78)	164(586)	217(195)	464(30)	564(12)
				HPAC				HPAC				CLIM

the comparison between the model and the operational forecast is on an inhomogeneous sample, the amount of improvement is very substantial. The model was not run for this ocean basin using real progs. However, assuming the decrease in accuracy using actual forecast fields would be on the same order as the Atlantic and the NW Pacific -- 20% at 48 hours and 30% at 72 hours - errors of 176 n mi at 48 hours and 282 n mi at 72 hours can be projected for all cases. Compared to the best operational techniques, these forecast errors translate to an improvement of 32% at 48 hours and 50% at 72 hours! At 24 hours, there is no degradation due to the use of actual forecast fields since they do not enter into the computation of the 24-hour forecast position. However, as shown for the Atlantic and NW Pacific, perturbing the best-track initial position to simulate warning position errors does have a strong impact on the 24-hour forecast position. Even using the worst case scenario of a northward track perturbation for all cases (which results in a 25% decrease in accuracy), the resulting improvement in the forecast error at 24 hours compared to HPAC is a very creditable 27%.

5.4 Synopsis and Summary

As mentioned earlier, the universal problem of all statistical-dynamical prediction models that use a perfect-prog approach to introduce prognostic data in the development of regression equations is the degradation in skill they suffer in operational use when actual forecast fields are used. In fact, other than NHC73, they do not attempt to forecast beyond 48 hours. Table 5.24 illustrates the amount of degradation that statistical-dynamical models suffer when they use actual forecast fields.

TABLE 5.24

A comparison of development and operational errors for selected statistical techniques. The developmental errors for NHC73, NHC72, and CLIPER are from Neumann and Lawrence (1973). The operational errors for NHC73, NHC72 and CLIPER are the entire sample errors from Neumann and Pelissier (1981). The errors for SNT are from Nomoto et al. (1976) and the errors for Keenan are from Keenan (1984).

	<u>24-HR</u>			<u>48-HR</u>			<u>72-HR</u>		
	DEV	OP	(OP-DEV)	DEV	OP	(OP-DEV)	DEV	OP	(OP-DEV)
NHC73	42	113	71	78	228	150	142	344	202
NHC72	68	113	45	175	257	82	308	375	67
CSU84A***	93	99	6	171	184	13	248	281	33
CSU84P****	77	84	7	146	164	18	205	257	52
SNT*	141	149	8	234	388	154	---	---	---
Keenan**	83	99	16	135	222	87	---	---	---

* SNT is statistical-dynamical model developed by Nomoto et al. (1976) for the NW Pacific in the vicinity of Japan.

** Keenan is statistical-dynamical model developed by Keenan (1984) for the Australian region.

***CSU84A is the Atlantic version of the new model using 500 mb steering. The errors were on a homogeneous sample for the period 1968-1981 and taken from Table 5.10A.

****CSU84P is the NW Pacific version of the new model using 500 mb steering. The errors were on a homogeneous sample for the period 1968-1981 and taken from Table 5.15A.

Note the relatively small amount of deterioration associated with CSU84. Although the degradation suffered by NHC72 is also comparatively small, NHC72 does not use prog data.

This large degradation in skill associated with statistical-dynamical schemes is in large part due to the over-reliance or overweighing of the "perfect" prognostic data at the expense of the analysis data. This problem was vividly shown earlier with the NHC73

predictor selection process that chose predictors from 36- and 48-hour forecast fields for the short-range 12- and 24-hour cyclone motion. As a result, although the model may produce very impressive results in development, when actual forecast fields that are obviously not as accurate as the verifying analysis fields are used operationally, the accuracy deteriorates rapidly. In certain instances where prognostic data are notoriously poor, as in the ocean region to the west of Australia, regression technique using just the analysis data outperforms one using prognostic data (T. Keenan, 1984).

The approach developed here attempts to circumvent this problem by discretizing 72 hours of cyclone motion into three shorter 24-hour time steps. This permits several important processes to occur:

- (1) the introduction of a revised persistence predictor after each 24 hours of motion
- (2) the opportunity to change the category relative to the ridge after each 24 hours of motion
- (3) the limiting of the reliance of the model on any one prognostic field to 24 hours of motion
- (4) the absence of any degradation for the 24-hour forecast since the first 24 hours of motion is based only on analysis fields
- (5) the updating of prognostic data relative to a new cyclone position -- not the initial cyclone position.

The advantages of this method over the recent customary method of applying prognostic data are obvious. If the prognostic fields are in error, there will be no impact on the 24-hour forecast position. In addition, since CSU84 does not use current motion as a predictor, an initial position error will have a much smaller effect on the 24-hour

forecast position than it will with, for example, NHC73 that does use current motion as a predictor. If the 24-hour forecast position is accurate, the updated persistence predictor as well as the ridge category in which to place the cyclone should be accurate. Then, even if the 24-hour forecast field is in error, the resulting 48-hour forecast position certainly will be more accurate than if the motion over 48 hours was calculated from the initial position. Also recall that half of the data needed to compute the height and pressure tendencies at the 24-hour forecast position to determine the 48-hour forecast position come from the analysis field. Thus, a solid forecast track for the early portion of the forecast period has been created on which to build the final 24 hours of motion to determine the 72-hour forecast position.

Comparable Skill of Model. In order to show skill in forecasting cyclone motion, a model's forecast accuracy must exceed that achieved by basic methods such as climatology and persistence. Neumann and Pelissier (1981) have proposed using the CLIPER model as a kind of normalizer or no-skill model to provide a benchmark on which to judge the skills of other models. They compute the percentage improvement or deterioration of a forecast as to how well the CLIPER forecast has done. This percentage is given by:

$$\% = 100 (E_c - E_m) / E_c.$$

where % is the percent improvement or deterioration over CLIPER forecast error, E_c is CLIPER forecast error and E_m is the model forecast error. Positive % indicates the model performed better than CLIPER, whereas negative % indicates the model performed poorer than CLIPER.

Figure 5.2 shows the relative skill of NHC73, which was the best overall performer among the operational models at the US National Hurricane Center, and CSU84. The north-of-ridge and on-the-ridge categories for CSU84 were combined to form the north zone since a cursory examination of those cases in the on-the-ridge category revealed that nearly all of the cases were north of 24.5°N . This version of the model used actual forecast fields with random perturbation of the initial position to simulate operational conditions as closely as possible for cyclone cases during 1973-1979.

Panel a presents the "all" cyclone category. It appears that relative to CLIPER, CSU84 possesses six times as much skill as NHC73 at 24 and 72 hours. It is also able to beat the official forecast by a wide margin at all forecast periods.

The most significant feature is shown on panel b where CSU84 is clearly superior to climatology and persistence at the longer forecast periods even in the south zone. While NHC73 is degrading rapidly between 48 and 72 hours, CSU84 is improving in performance.

Finally, panel c compares the relative performance on cyclones in the northern zone. The strength of any statistical-dynamical model should emerge in this category and indeed NHC73 and CSU84 performed better than CLIPER by the largest margin in this zone. The relative skill of CSU84 appears to be nearly twice that of NHC73 for this category.

Figures 5.3 through 5.5 offered a graphic comparison of the relative skill of CSU84 and NHC73 for the three categories in the Atlantic. As shown in panel a of Fig. 5.2 and again in Fig. 5.3, CSU84

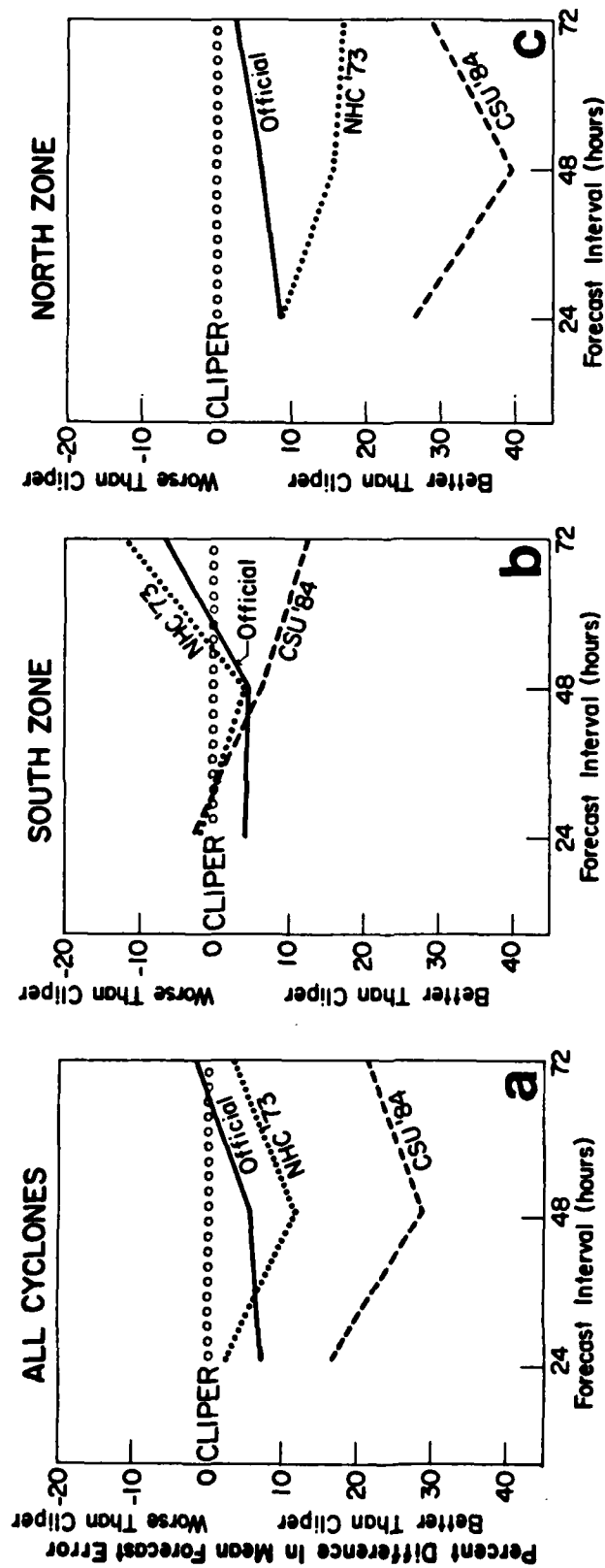


Fig. 5.2. Performance of specified models relative to performance of CLIPER model on (a) entire sample of cyclones, (b) south zone cyclones and (c) north zone cyclones. Sample is nearly homogeneous over years 1973-1979. Forecast errors for CLIPER, NHC73 and official are from Neumann and Pelissier (1981).

ATLANTIC ENTIRE SAMPLE (1973-79)

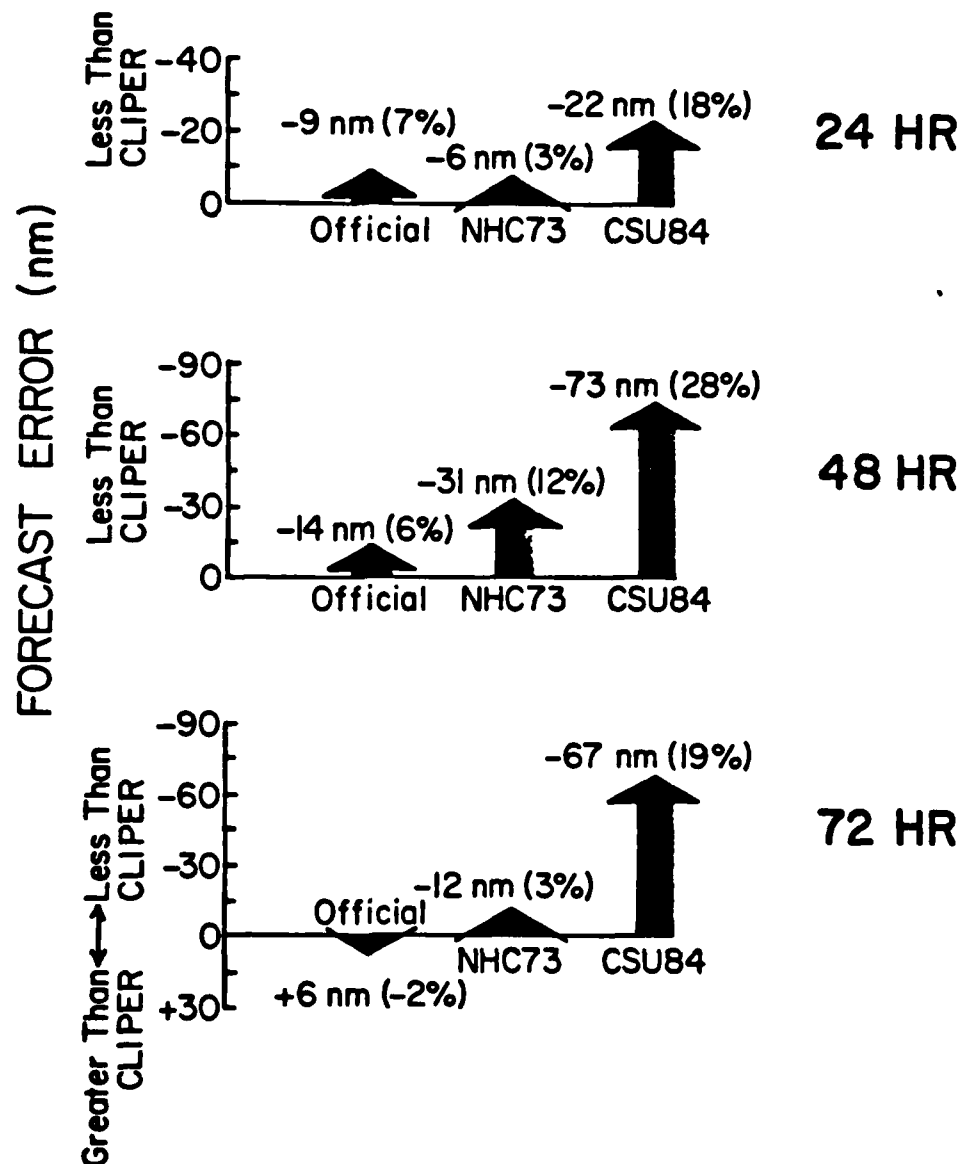


Fig. 5.3. Relative skill of CSU84 compared to NH73 using CLIPER as a no-skill model to provide a benchmark. Decrease or increase in the forecast error over CLIPER is shown with the percent improvement in parentheses for Atlantic entire sample. Errors for NHC73 and official are from Neumann and Pelissier (1981).

ATLANTIC SOUTH ZONE (1973-79)

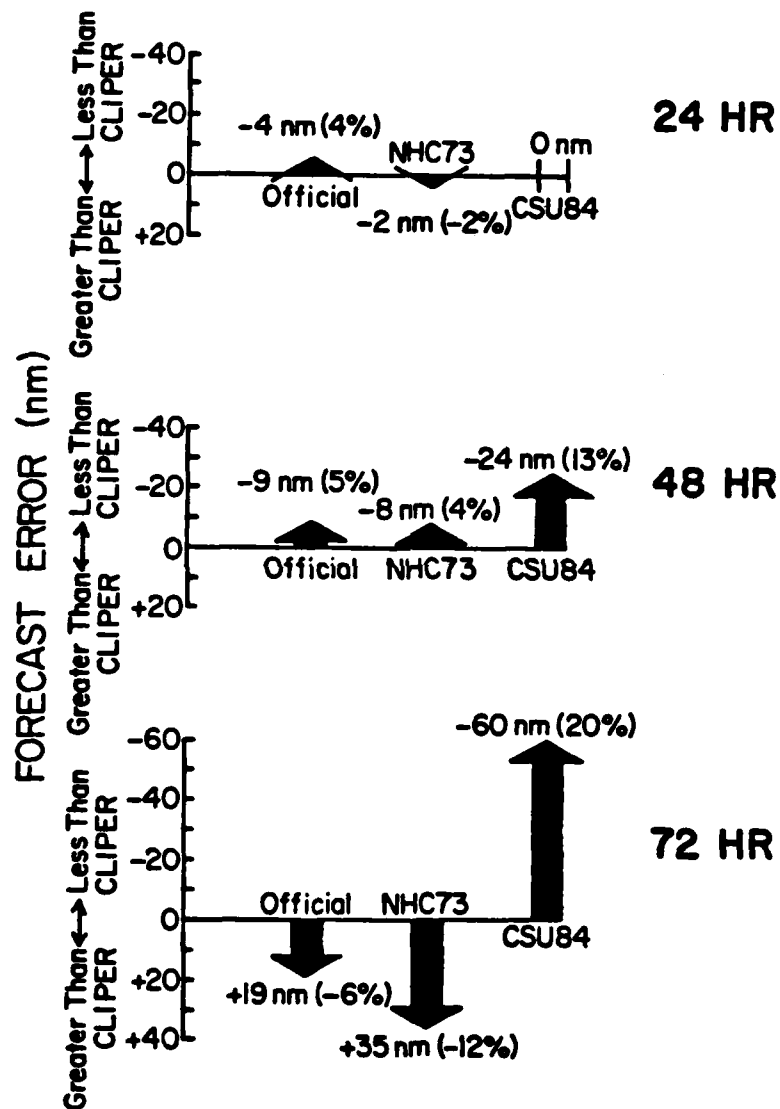


Fig. 5.4. Same as Fig. 5.3 except for Atlantic south zone.

ATLANTIC NORTH ZONE (1973-79)

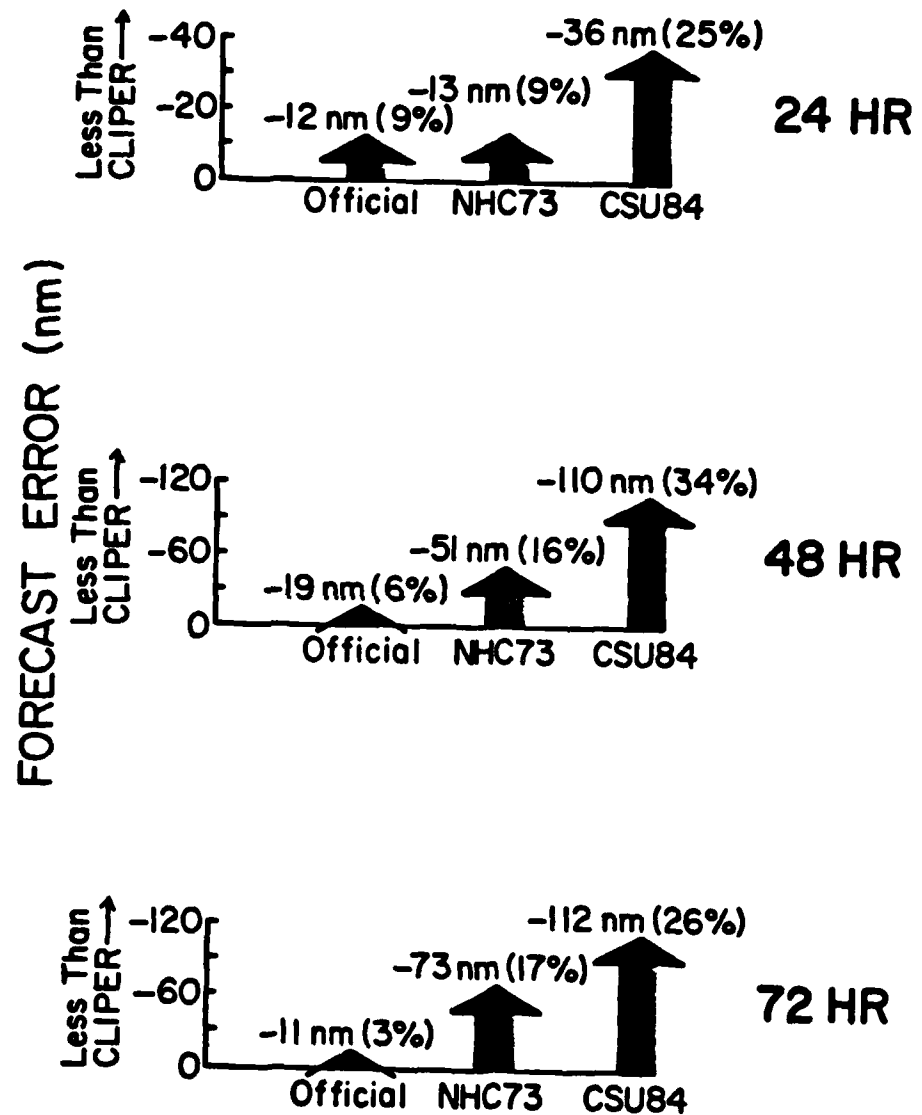


Fig. 5.5. Same as Fig. 5.3 except for Atlantic north zone.

is six times as skillful as NHC73 relative to CLIPER at both the 24- and 72-hour forecast periods for the entire sample. CSU84's high skill at the 24-hour period comes primarily from its strong performance on north zone cyclones (see Fig. 5.5) while the skill at 72 hours comes largely from its performance on south zone cyclones (see Fig. 5.4).

The model's encouraging performance on north zone cyclones appears to be related to its ability to accurately depict and anticipate changes in the synoptic and steering forcings as a result of the ridge stratification and the 24-hour time steps. The short time steps permit the category the cyclone is placed relative to the ridge to change as it becomes necessary. The model's ability to provide accurate position forecasts at the longer periods for the south zone is similarly related to the segmented 24-hour time steps which permits the reintroduction of updated persistence at each step.

A similar comparison for the NW Pacific was done using HPAC as the normalizer or no-skill model to provide the benchmark for comparison. The forecast error data used for this comparison are from NEPRF (T. Tsui, personal communication) and appear in Fig. 5.6 and 5.7.

The relative skill of CSU84 compared to the two best overall performers in the NW Pacific (OTCM and NTCM) is considerable and the apparent improvement in forecast error provided by CSU84 is encouraging. The model was at least four times as skillful as the best operational technique (OTCM) at all forecast periods. As in the Atlantic, the ridge stratification and the 24-hour time steps are believed to provide a method for the model to optimally formulate the current synoptic state and its changes that affect cyclone movement over a 24-hour time span.

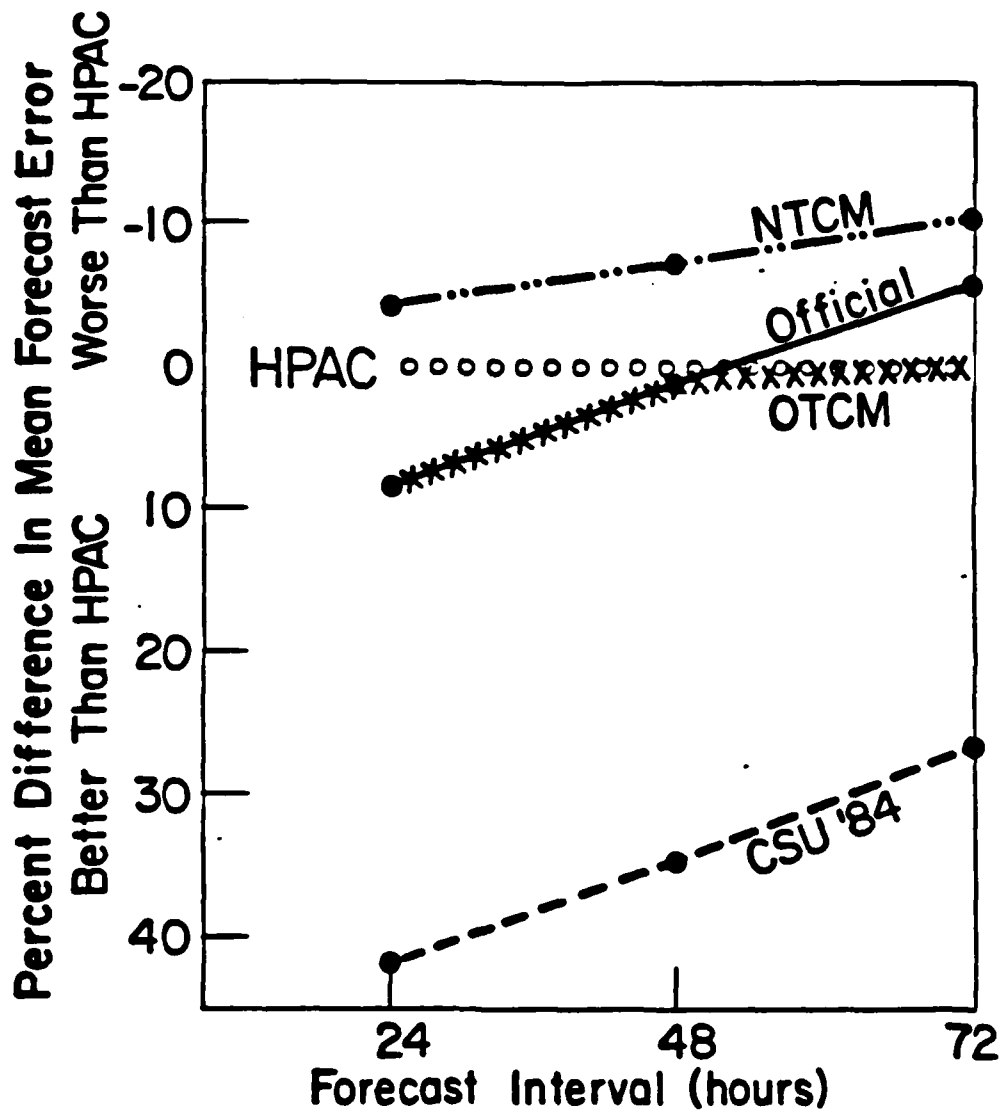


Fig. 5.6. Performance of specified models relative to performance of HPAC on NW Pacific cyclones. Sample is nearly homogeneous over years 1979-1981. Forecast errors for official, HPAC, NTCM and OTCM are from Tsui (personal communication).

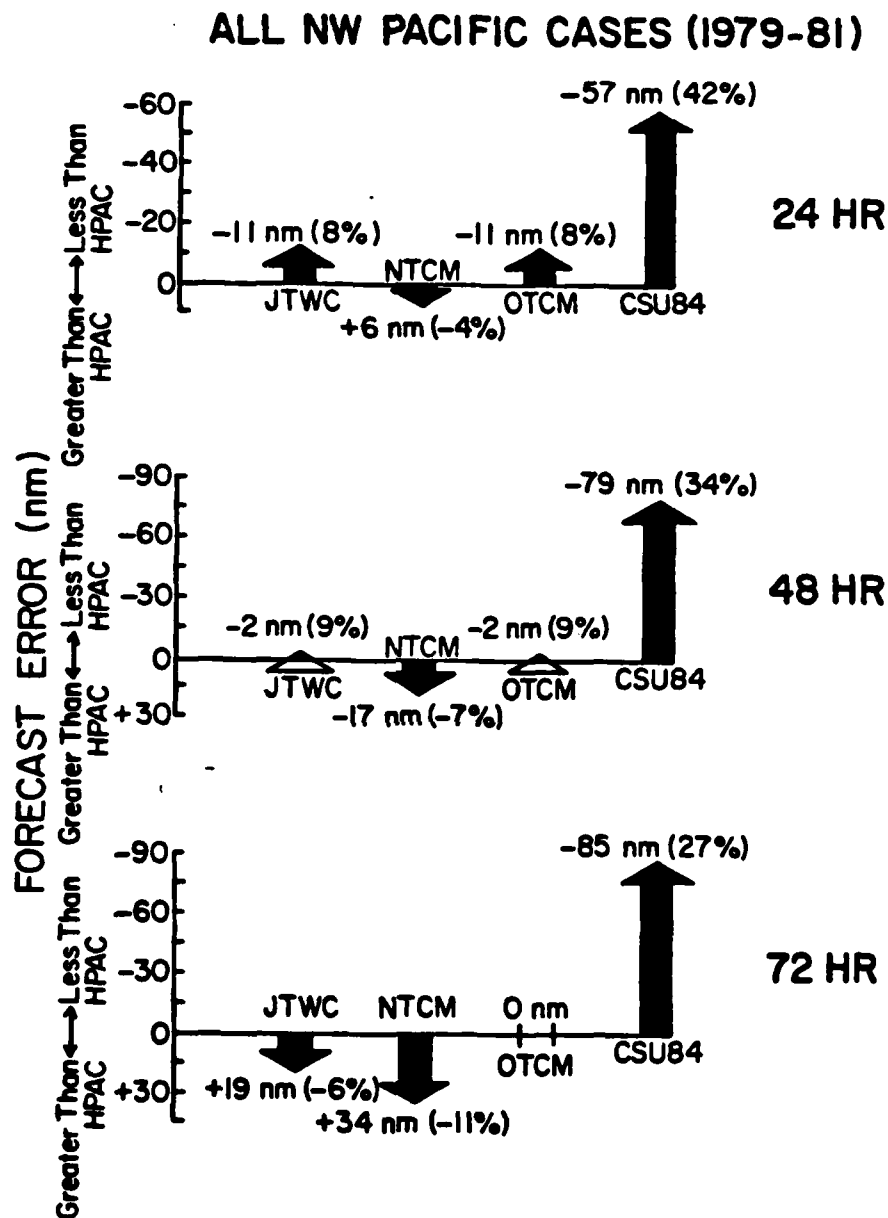


Fig. 5.7. Relative skill of CSU84 for the NW Pacific compared to OTCM and NTCM using HPAC as a no-skill model to provide a benchmark. Decrease or increase in the forecast error over HPAC is shown with the percent improvement in parentheses. Errors for OTCM, NTCM and JTWC are from NEPRF (T. Tsui, personal communication).

Figures 5.8 and 5.9 for the Atlantic and NW Pacific, summarize the results of the various attempts to simulate operational conditions in comparison with operational forecast models. The perfect-prog runs for CSU84 are shown along with the runs using actual progs as well as the runs with both actual progs and pseudo-warning positions. Note that the CSU84 forecast errors from the operational simulation runs lie closer to the perfect-progs than to those of the other operational models. This appears to strongly indicate that CSU84 is capable of improving one- to three-day track predictions in the operational arena.

Based on the CSU84 forecast errors for the Atlantic and NW Pacific, it would appear that cyclones in the Atlantic basin are more difficult to forecast. A cursory examination of the number of forecast situations in each of the three categories relative to the ridge indicates that in the NW Pacific, the south-of-ridge cases dominate with a sizeable number in the on-the-ridge category. Relatively few cases occur north of the ridge. For the Atlantic, the situation is reversed. The number of cases north of the ridge is almost as much as the number to the south with relatively few cases on the ridge.

The reason for the observed difference in cyclone tracks for the two ocean basins is due to differences in climatology. Majority of cyclones in the NW Pacific form at a lower latitude than those in the Atlantic. Hence, Pacific cyclones have a tendency to track poleward for greater distances prior to recurving eastward than cyclones in the Atlantic. Following recurvature, shearing or extratropical transition follows rather quickly. Atlantic cyclones, on the other hand, come under

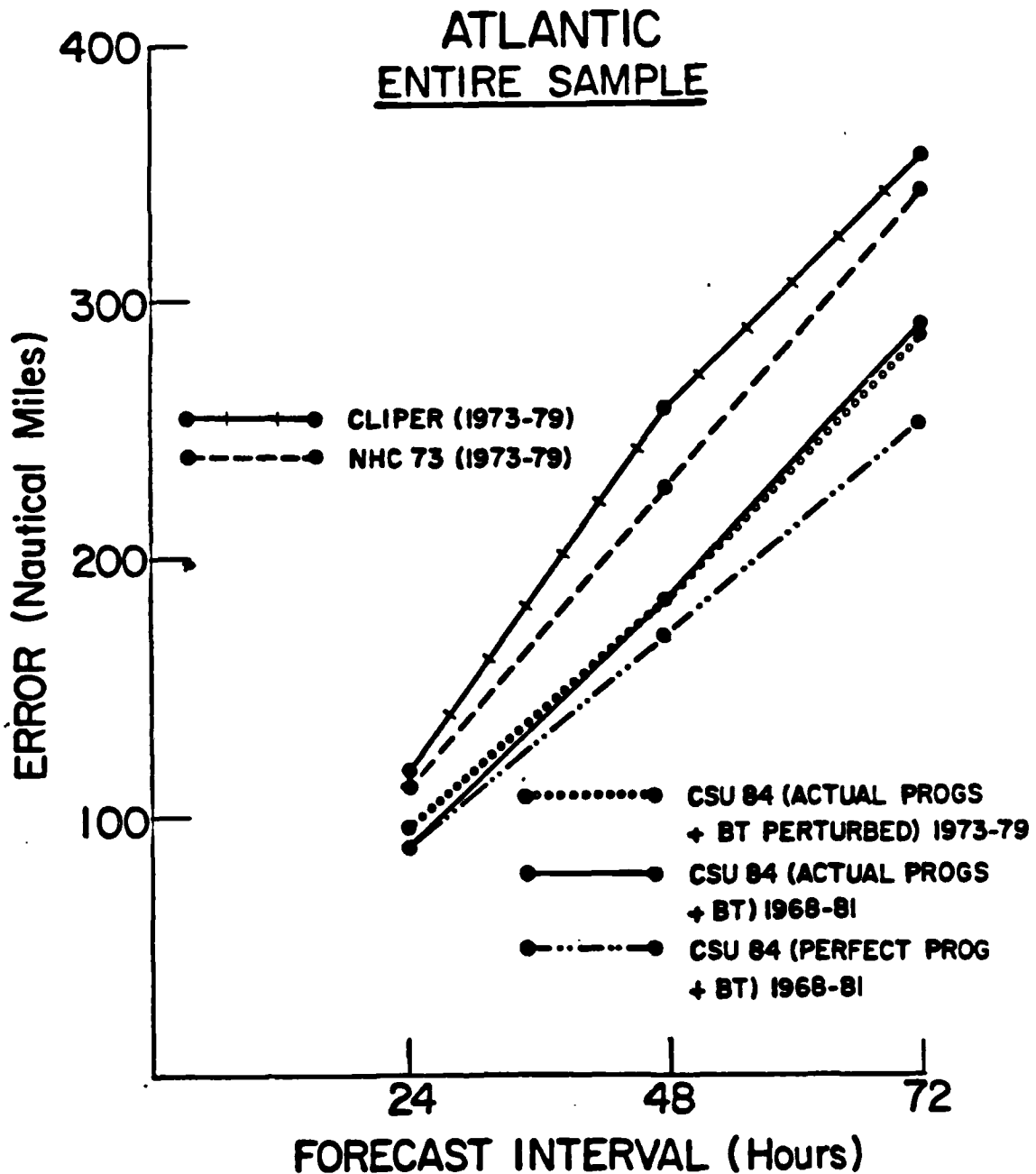


Fig. 5.8. Mean Atlantic forecast error (n mi) for the various CSU84 runs compared to CLIPER and NHC73 at 24, 48 and 72 hours. Errors for CLIPER and NHC73 are for 1973-1979 entire sample and are taken from Neumann and Pelissier (1981). One of the CSU84 runs denoted by ooooooooooooo is for 1973-1979. The other runs are for 1968-1981.

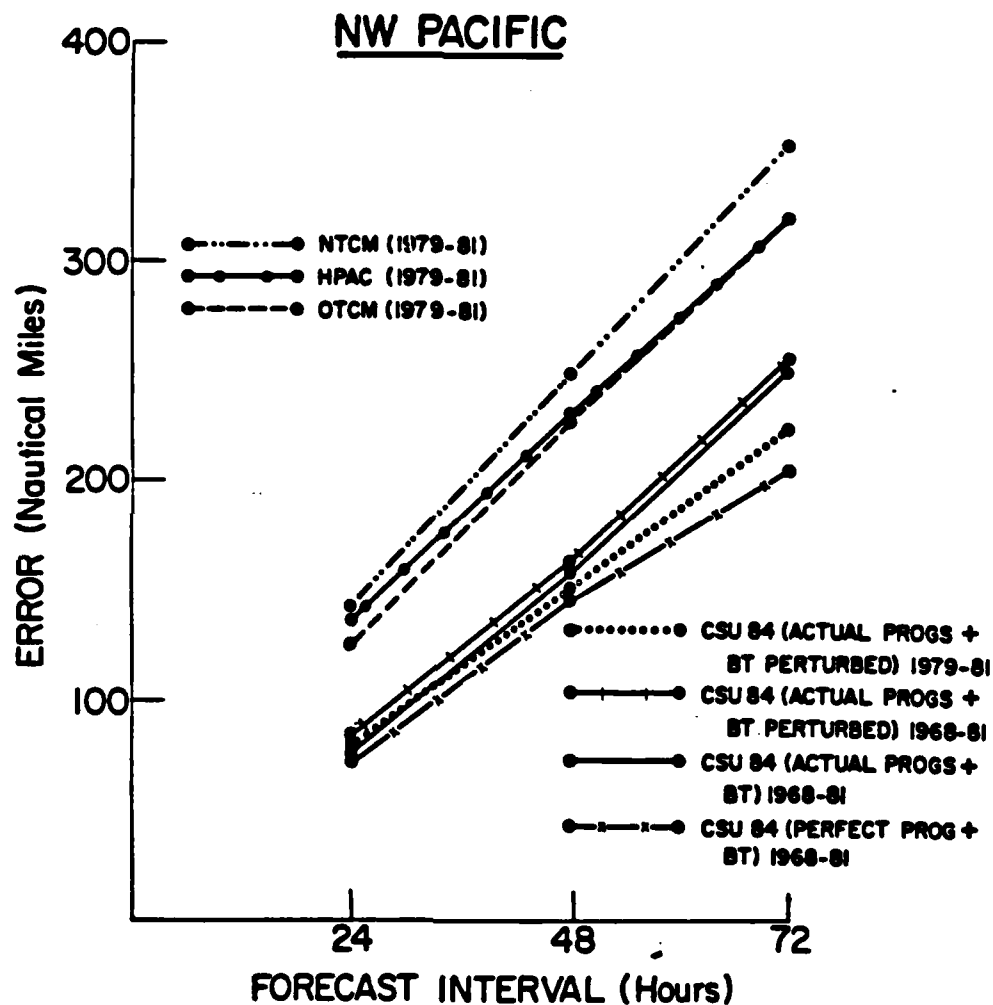


Fig. 5.9. Mean NW Pacific forecast error (n mi) for the various CSU84 runs compared to HPAC, OTCM and NTCM at 24, 48 and 72 hours. Errors for HPAC, OTCM and NTCM are for 1979-1981 and were provided by NEPRF (T. Tsui, personal communication). One of the CSU84 runs denoted by ooooooooooooo is for 1979-1981. The other runs are for 1968-1981.

the influence of mid-latitude westerlies before tracking very far poleward and the portion of their track that would fall into the on-ridge category is relatively small.

In addition, as shown by Xu and Gray (1982) the percentage of cyclones undergoing fast (> 7.5 m/s), slow (< 2.5 m/s) or looping motion is much higher overall in the Atlantic than in the NW Pacific. Figure 5.10 is taken from the work of Xu and Gray (1982) to illustrate the difference. Due to the large number of fast-moving cyclones at low latitudes and the large number of slow-moving and looping cyclones at higher latitudes, along with the relatively small number of cases, the average forecast errors become inflated by these difficult forecast situations.

In view of these difficult forecast cases, the quite skillful performance of CSU84 in the Atlantic is particularly noteworthy. In the NW Pacific and North Indian Oceans where a statistical-dynamical model is not available, the potential for a large improvement in track forecast accuracy looks very promising.

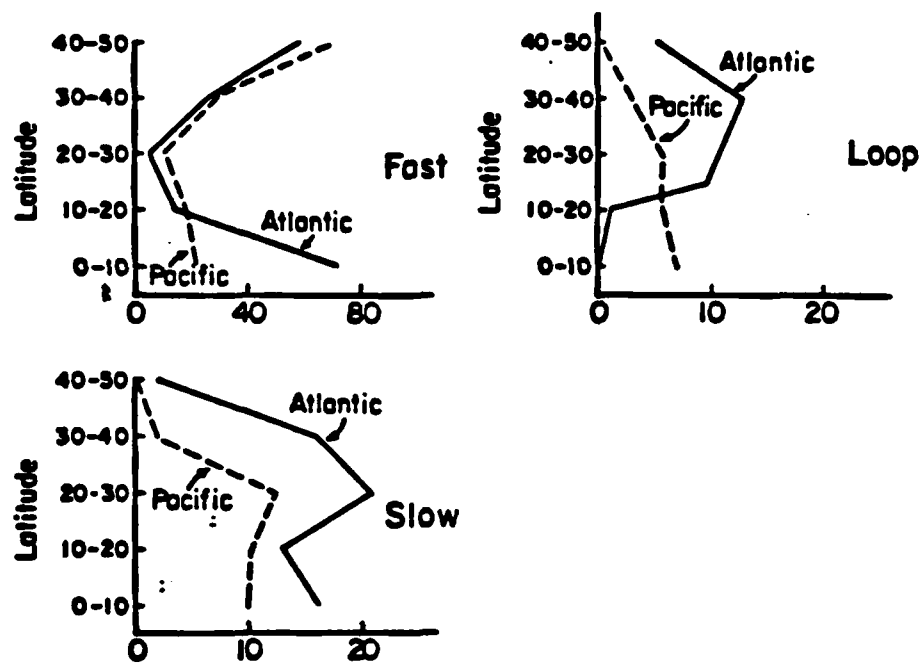


Fig. 5.10. Percentage of storms in the Atlantic and western North Pacific which are fast (> 7.5 m/s), slow (< 2.5 m/s) or looping vs. latitude. (From Xu and Gray, 1982).

6. CONCLUSION

Although significant progress has been made in developing statistical and dynamical models for forecasting the tracks of tropical cyclones, the forecast errors over the past decade have shown little improvement. The lack of observations over the data-sparse regions of the tropical oceans, and the resulting difficulty of accurately specifying the initial state of the atmosphere for both the dynamical tropical cyclone models and the global PE models, have most often been cited for the lack of improvement. "Give me more observations and better analyses and I'll give you better track forecasts" has been the motto for the last few years.

This adage of requiring better analyses is certainly true, but another important consideration to improving the accuracy of statistical track prediction models is the proper application of the existing data. The need for synoptic data, especially in a prognostic sense, to be able to forecast cyclone motion at the longer forecast periods and to predict anomalous motion is well known. However, the statistical-dynamical models in existence that incorporate the output from a numerical model as one set of predictors apply the prognostic data always from the initial position of the cyclone to the desired forecast projection of 12, 24, 36, 48, or 72 hours. The inherent weakness of using prognostic data in such a manner was shown by comparison with the results from this newly developed model using an approach of introducing prognostic

data relative to each new cyclone position as if they were analysis data.

The suggested new method of applying the various climatological, persistence and synoptic predictors is patterned after the normal procedure followed by operational forecasters as they subjectively formulate the forecast track. This process normally begins with an examination of the current and 24-hour old analysis fields relative to the initial position of the cyclone. Synthesis of the synoptic information combined with persistence produces a short-range 24-hour forecast motion. The 24-hour forecast field is only then introduced to provide an updated environmental influence on the cyclone relative to the new position and the cyclone is projected forward another 24 hours. The 48-hour forecast field is then used to provide the environmental forcings relative to the cyclone's projected 48-hour forecast position. New persistence information is also formulated relative the latest cyclone position and the final 24 hours of motion is projected.

Although the scheme proposed here was developed with an emphasis on improving the forecast accuracy for cyclones at the higher latitudes and at the longer forecast periods, it performs at the lower latitudes and at the shorter forecast period with significant skill. As shown in Chapter 5, the degradation in skill resulting from the use of actual forecast fields was minimal compared to that suffered by the other discussed statistical-dynamical models.

The increase in forecast errors between the perfect-prog and the actual prog cases for the three other statistical-dynamical models that were examined ranged from 87 n mi to 154 n mi at 48 hours compared to

less than 20 n mi for CSU84. What's more, two of these models do not attempt to forecast beyond 48 hours.

A comparison of the model under a simulated operational setting on a nearly homogeneous sample in comparison with the best operational techniques in the Atlantic and NW Pacific using climatology and persistence as a normalizer to indicate the relative skill of the models as compared to a no-skill forecast was presented in Chapter 5. The comparison indicated the strength of the new scheme at both the shorter 24-hour forecast period and the longer 72-hour forecast period. For the entire Atlantic sample, CSU84 is six times as skillful as NHC73 relative to CLIPER at both the short and long forecast times. CSU84's relatively high skill at the 24-hour period comes primarily from its strong performance on north zone cyclones while the skill at 72 hours comes largely from its performance on south zone cyclones.

The model's encouraging performance on north zone cyclones appears to be related to its ability to accurately depict and anticipate changes in the synoptic and steering forcings as a result of the ridge stratification and the 24-hour time steps. Its ability to provide accurate position forecasts at the longer periods for the south zone is similarly related to the segmented 24-hour time steps which permits the reintroduction of persistence at each step.

Equally strong performance of CSU84 in the NW Pacific was evident. The model was at least four times as skillful as the best operational technique (OTCM) at all forecast periods. Again, the ridge stratification and the 24-hour time steps are believed to provide a method for the model to formulate the current synoptic state and its changes that affect cyclone movement over a 24-hour time span.

The key to this large improvement in accuracy lies in the unique application of the predictors normally used in statistical prediction models. Climatology is incorporated via a stratification scheme based on the position of the cyclone relative to the 500 mb subtropical ridge. Each cyclone forecast situation is initially stratified by one of three categories relative to the 500 mb ridge -- south-of-ridge, on-the-ridge, or north-of-ridge -- and the appropriate regression equations are used to calculate the 24-hour displacement. The 72-hour forecast period is segmented into three 24-hour time steps and the 24-hour displacements are stepped off until the desired multi-day forecast projection is reached. This permits the introduction of updated persistence and synoptic predictors relative to the new cyclone position as well as the opportunity to change the stratification category as it becomes necessary based either on the past direction of motion or on the judgment of the forecaster. Two hundred millibar geostrophic winds 5° to 20° northwest and north of the cyclone are used as key steering predictors in the Atlantic and in recurvature situations for strong typhoons in the NW Pacific. Five hundred millibar steering predictors proved to be more accurate for all other situations in the NW Pacific, however.

An additional advantage of a prediction model such as this is the ease with which it can be applied directly at operational locations and aboard ships without a link to a large computer data base. The initial analyses and the 24- and 48-hour forecast fields of sea level pressure and 500 mb and 200 mb geopotential heights are all that is required. Further, since the model permits forecaster intervention in computing the forecast positions, the operational forecaster could easily modify

the synoptic predictors required for input if the analysis or prognostic field appears to be in error. The forecaster could also make his own forecast fields based on subjective extrapolation of large-scale synoptic patterns in the areas where predictors are required.

This discretized forecast method revealed the significant contribution to the forecast of the steering predictors on 24-hour motion at the higher latitude in the Atlantic. For the NW Pacific, steering predictors had a strong impact only for east-west motion north of the ridge and only at the 200 mb level. The motion of south-of-ridge cyclones was dominated by persistence whereas the motion of on-the-ridge category cyclones was strongly influenced by the synoptic predictors, primarily the current 500 mb heights. For the North Indian Ocean, cyclone motion south of the ridge was dominated by persistence. However, cyclone motion on or north of the ridge was strongly dependent on synoptic predictors, primarily the 24-hour tendency of surface pressure.

Incremental improvement in the accuracy of this model can likely be made by several smaller modifications. It is felt, however, that the major improvement was gained by the special methodological approach developed in this paper.

One obvious source of improvement is to redevelop the regression equations for use in the NW Pacific and North Indian Oceans using synoptic data from the Navy Fleet Numerical Oceanography Center (FNOC) rather than the NMC data used to develop the CSU-84 equations. Harrison (1982), while comparing the NTCM and MFM, discovered considerably degraded performance for the NTCM when it was initialized with NMC analysis rather than FNOC tropical analysis. An initialization

procedure that resulted in much smaller amplitude of the zonal wind features in the NMC data (greatest in the lower 1000-850 mb levels) was suspected as the primary reason. Redevelopment of the regression equations using the FNOC data was the projected plan if the degradation using the Navy prognostic fields had been severe. Since it was not, the plan to redevelop the equations was abandoned. However, since the statistical characteristics of the two data sources differ, one would expect better model performance if it used the same data source in operational use that it used in development. The fact that the deterioration in the accuracy of the model was as small as it was is certainly encouraging.

The ideal method of developing the regression equations, as alluded to in Chapter 2, is to use the MOS approach and use the actual forecast fields instead of analysis fields. This would certainly be possible for the NW Pacific since there are adequate cyclone cases and the forecast fields for the surface and 500 mb level are available since 1968. The degradation in skill from the development to the operational fields then primarily would be eliminated. This may now be more difficult, however, since the Navy has abandoned its hemispheric PE model and is now using a global spectral model.

A second source of possible improvement to this scheme would be the substratification of the development set to separate those cyclones with very fast motion (>7.5 m/s) from those with very slow (<2.5 m/s) motion. An attempt along this line was made and alluded to in Chapter 3. However, the method of separating these two classes of cyclones was poor and the results were discouraging. Better results could probably be achieved if, as mentioned in Chapter 5, a larger threshold value of

positive or negative 500 mb height pattern indicator was used and the resulting fast and slow equations were used on only those cyclones that exhibited fast or slow motion based on, for example, their past 12-hour motion. Instead, in the aborted method attempted here, all cyclones used either the fast or slow equations and this is probably where the scheme failed. The only problem with the suggested substratification is the small sample size that might result for the very fast and very slow subsets.

Other improvements may be possible by changing the grid for computing the geostrophic winds from the geopotential height gradients. This model used a diamond grid with grid points north, south, east, and west 5° away from the point where the steering wind was being computed. Patterns other than a diamond or distances greater than 5° could be tested. The use of actual observed winds rather than height gradients should be tested although the use of wind field data did not seem to produce any significant impact on forecast errors when compared to the use of height field data for Southern Hemisphere statistical-synoptic schemes (Keenan, personal communication).

In any event, CSU84 - as developed and detailed in this paper - appears to offer very encouraging verification results and appears to produce significant improvement in forecast skill. The amount of reduction in forecast position errors suggested by these results should, hopefully, hasten the testing of the model in an operational environment.

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APPENDIX A

List Of All Objective Techniques Currently In Operational Use

Atlantic

- HURRAN - HURricane Analog system uses analog cyclones in a time and space window similar to the current cyclone to generate forecast track. (Hope and Neumann, 1970)
- CLIPER - CLimatology and PERsistence system is a purely statistical technique that uses climatology and persistence information as predictors to generate regression equations using essentially the same predictors used in the analog sense by HURRAN. (Neumann, 1972)
- NHC67 - statistical-synoptic system that uses linear combinations of observed height and height change fields at the 1000, 700, and 500 mb surfaces as predictors for zonal and meridional components of cyclone motion. Persistence is also used for the early forecast periods. (Miller, et al., 1968)
- NHC72 - combines output from HURRAN, CLIPER and NHC67 into one forecast using a modified stepwise screening technique. (Neumann, et al., 1972)
- NHC73 - combines output from CLIPER, a steering subset using height gradients and thicknesses and a synoptic subset that introduces 24-, 36-, and 48-hour 500 mb prognostic height data into one forecast using an optimized geographical stratification system. (Neumann and Lawrence, 1973)
- SANBAR - SANders BARotropic model is a filtered barotropic model using observed 1000 to 100 mb pressure weighted winds. The wind field near the cyclone is modified to conform to the observed cyclone motion. (Sanders and Burpee, 1968)
- MFM - Moveable Fine Mesh baroclinic model has 10 vertical levels and 60 km horizontal grid spacing. (Hovermale and Livezey, 1977)

NW Pacific, South China Sea, and N Indian Oceans

- TYAN - TYphoon ANalog system uses analog cyclones with similar time and space characteristics to generate 24, 48, and 72 hour forecast positions. (Jarrell and Somerville, 1970)

- CY50 - CYclops 500 is an updated HATTRACK/MOHATT steering program that provides geostrophic steering forecasts at the 500 mb level using prognostic fields and a 12-hour persistence bias. (Renard, 1968; Renard, et al., 1973)

- CLIM - CLIMatology aid that provides forecast positions based upon the month and position of the current cyclone.

- HPAC - Half Persistence And Climatology provides 24- and 48-hour forecast positions that are the mid-points of straight lines connecting the 24- and 48-hour forecast points on the XTRP and CLIM tracks.

- XTRP - EXTRaPolation forecast that extropolates a straight line from the 12-hour old position to the current position.

- BPAC - Blended Persistence And Climatology provides 24-, 48-, and 72-hour forecast positions with less weight being given to persistence at each succeeding forecast interval.

- NTCM - Nested Tropical Cyclone Model is a primitive equation model with 3 vertical levels and a 41 km grid centered on the cyclone that moves within a coarser grid. (Harrison, 1981)

- OTCM - One-way Tropical Cyclone Model is a three-layer primitive equation model with a 205 km horizontal grid. Navy hemispheric prog fields are used at 12-hour intervals to update the model's boundaries. (Hodur and Burk, 1978)

APPENDIX B

Correlation coefficients fields for the Atlantic on-the-ridge and south-of-ridge categories.

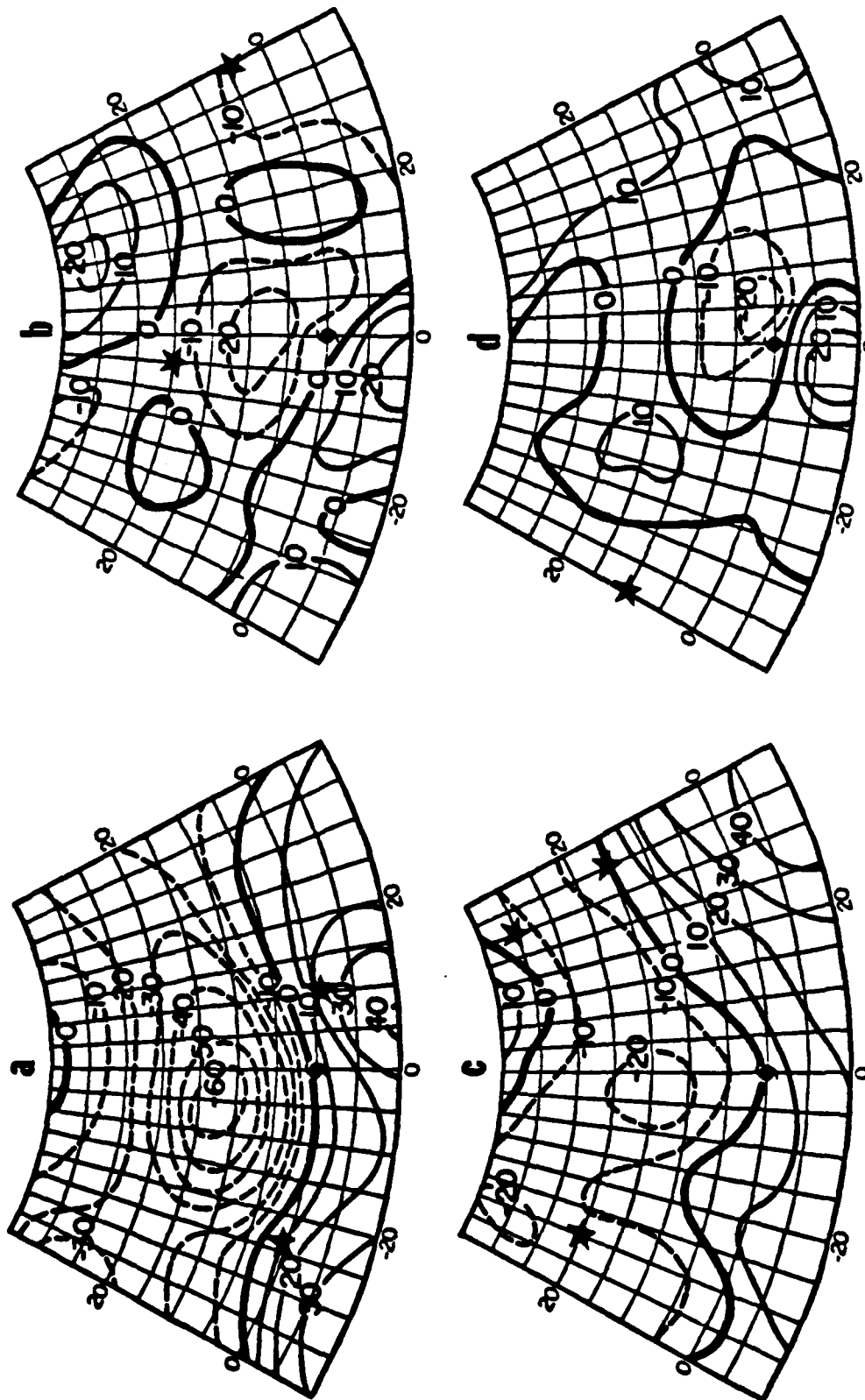


Fig. B.1. Correlation coefficient fields ($\times .01$) for the Atlantic on-the-ridge fast U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\bullet) and the stars indicate the gridpoints at which predictors were selected.

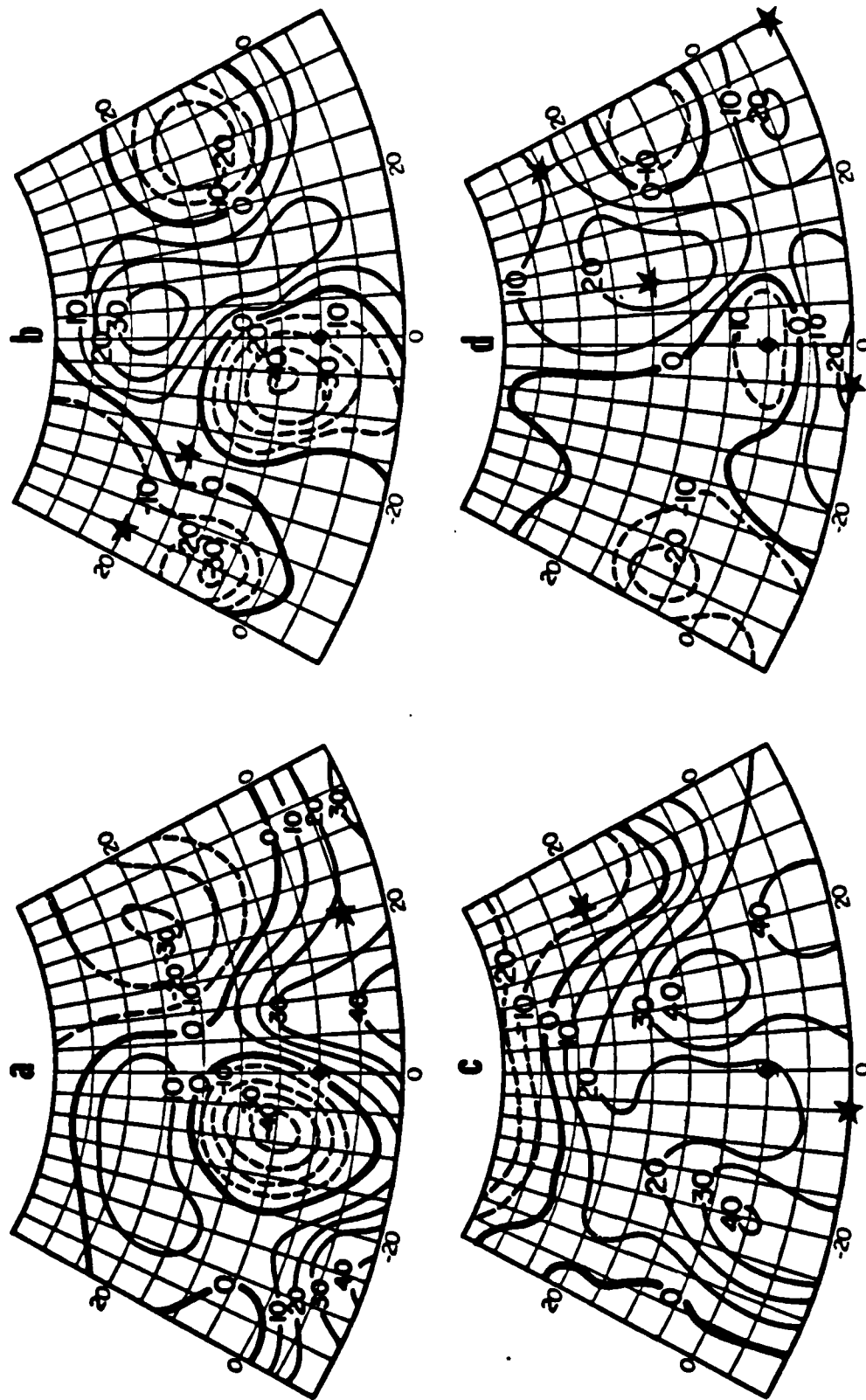


Fig. B.2. Correlation coefficient fields ($\times .01$) for the Atlantic on-the-ridge fast V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\bullet) and the stars indicate the gridpoints at which predictors were selected.

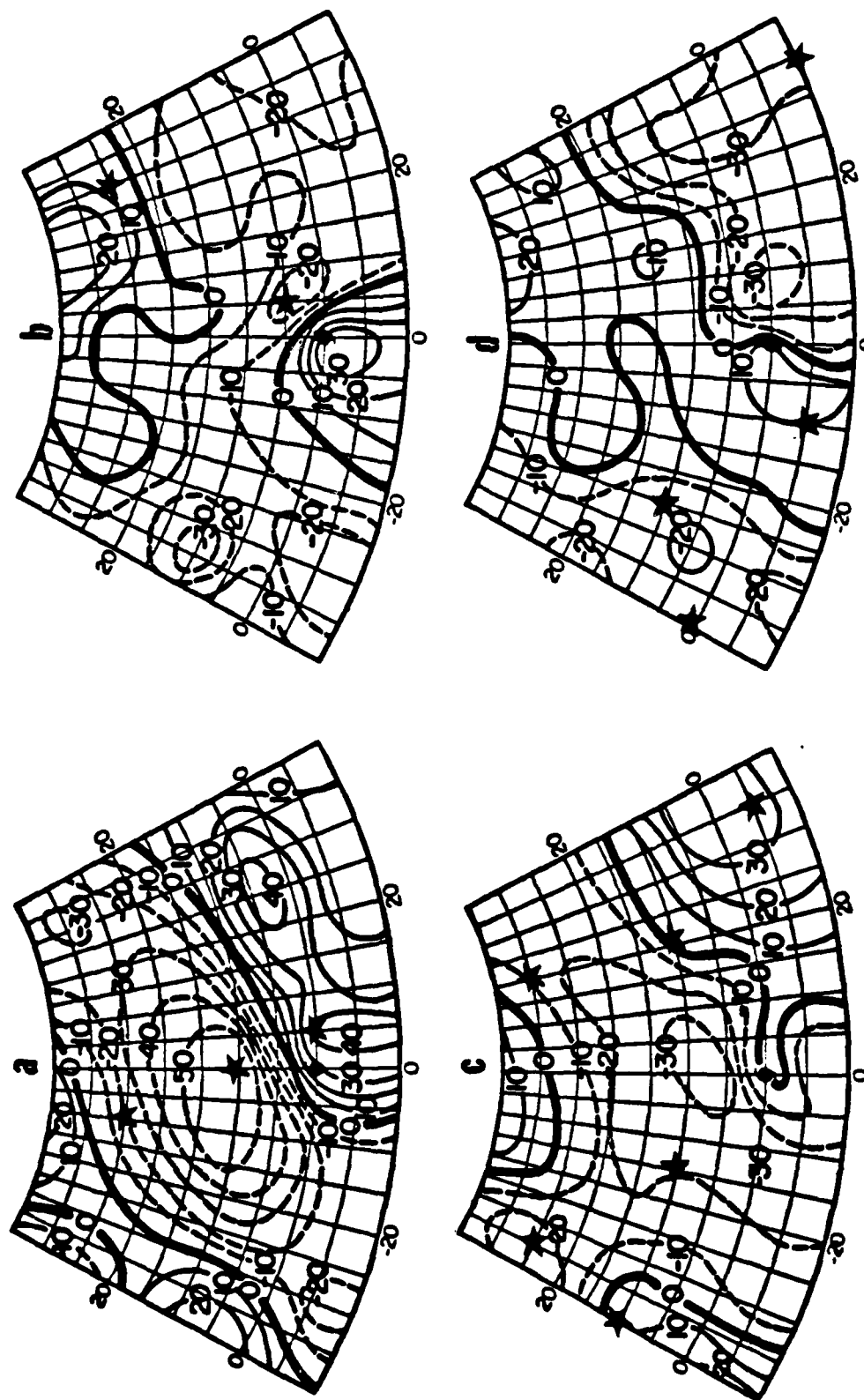


Fig. B.3. Correlation coefficient fields ($\times .01$) for the Atlantic on-the-ridge slow U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (ϕ) and the stars indicate the gridpoints at which predictors were selected.

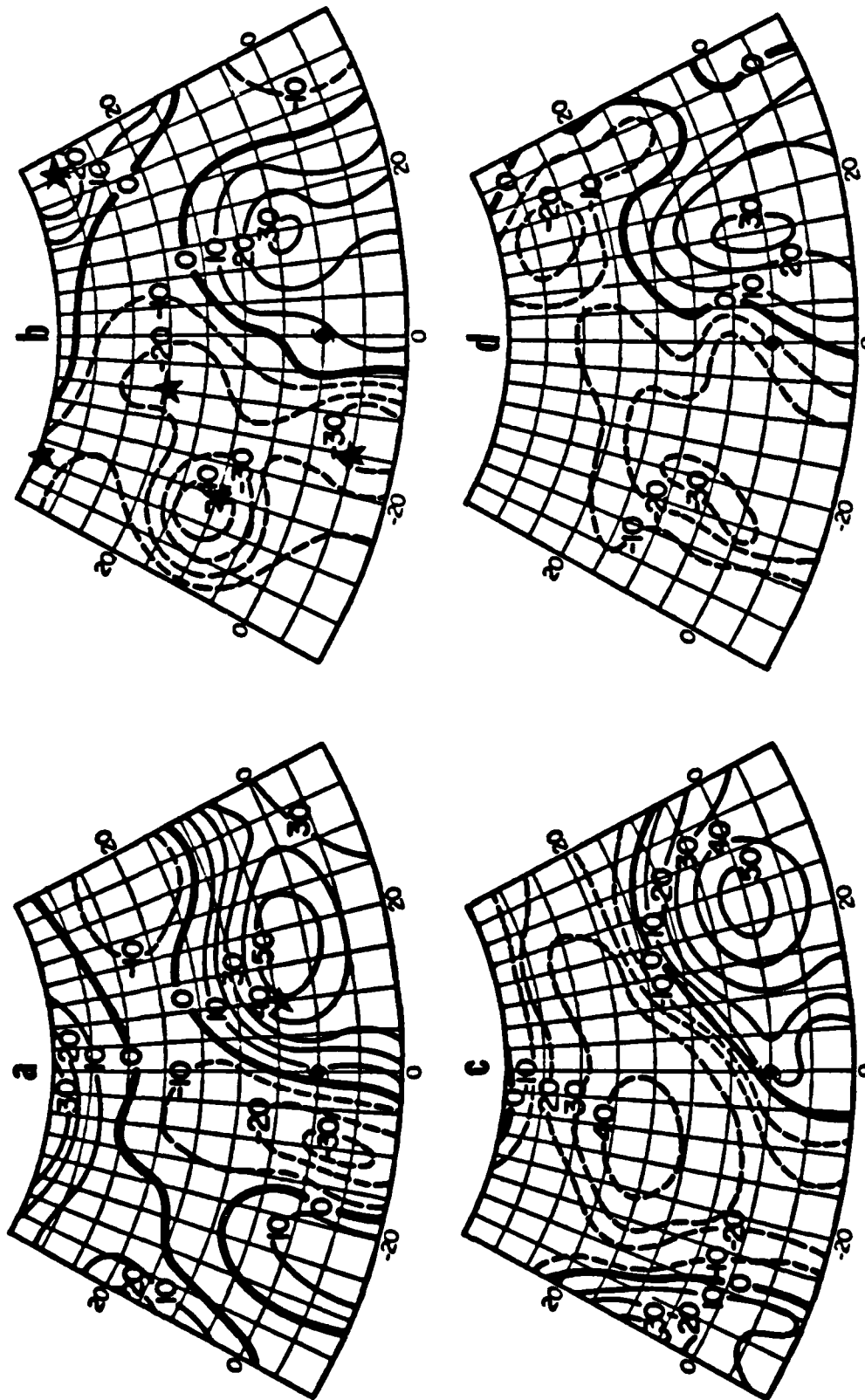


Fig. B.4. Correlation coefficient fields ($\times .01$) for the Atlantic on-the-ridge slow V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\bullet) and the stars indicate the gridpoints at which predictors were selected.

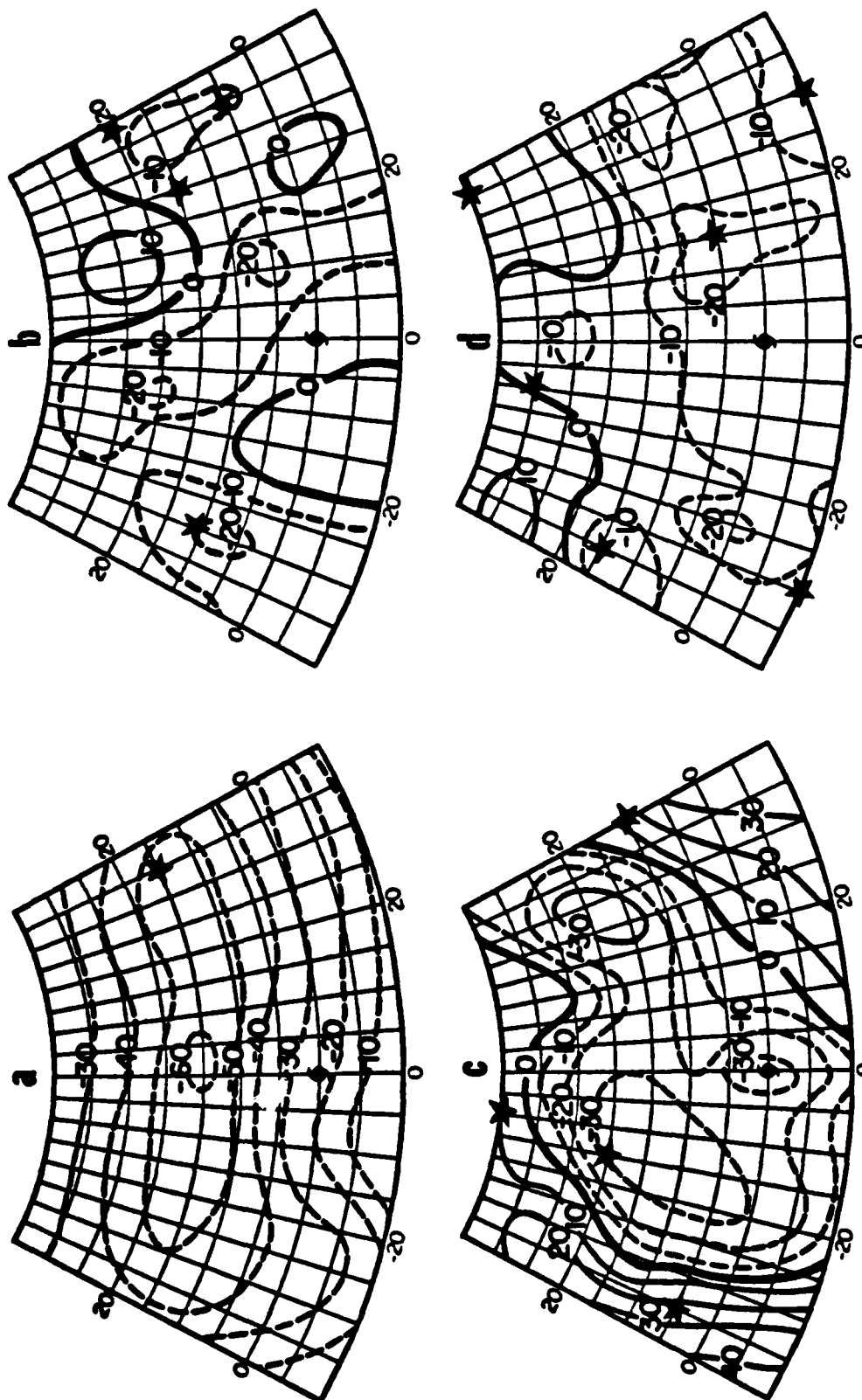


Fig. B.5. Correlation coefficient fields ($x .01$) for the Atlantic south-of-ridge fast U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\odot) and the stars indicate the gridpoints at which predictors were selected.

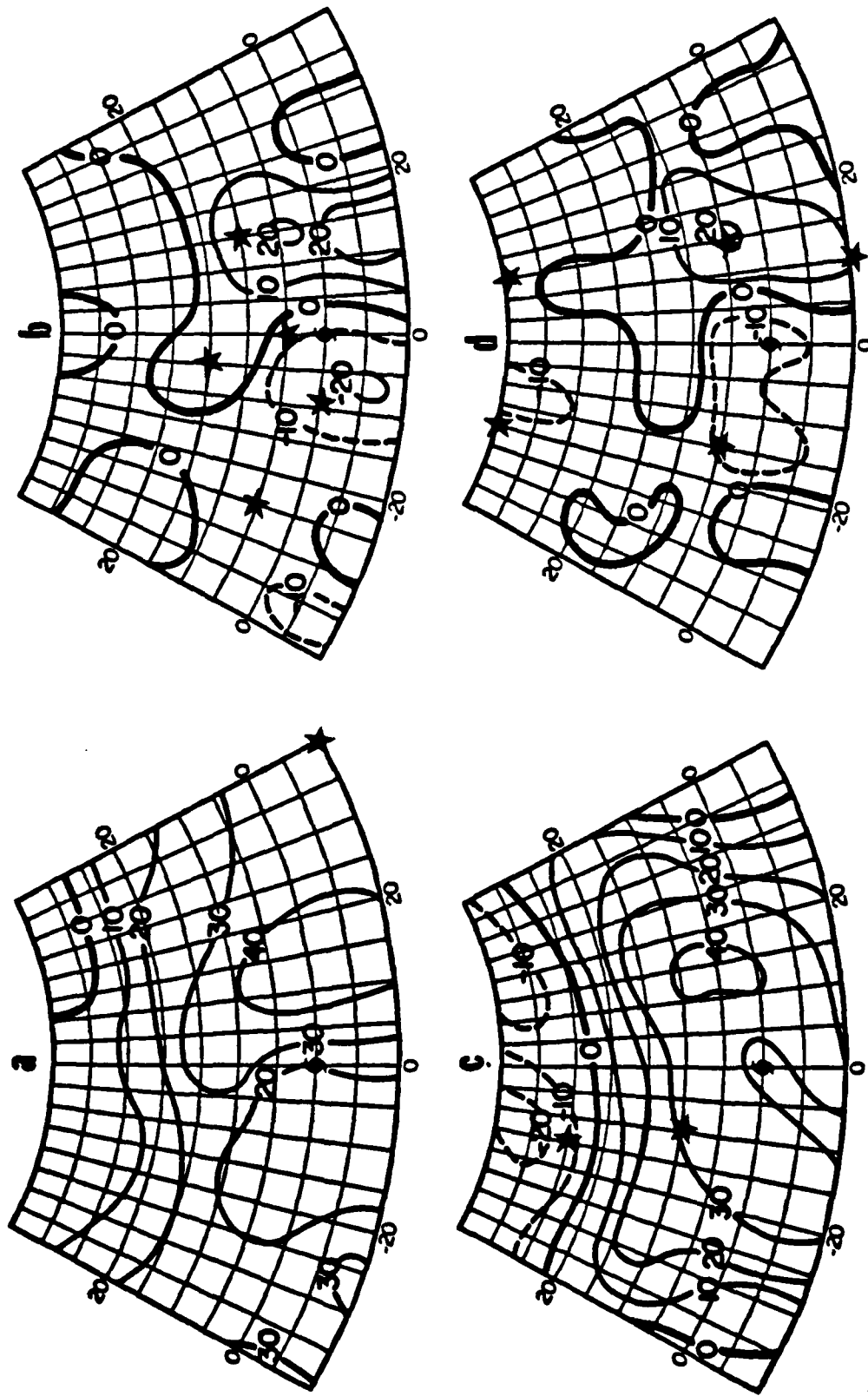


Fig. B.6. Correlation coefficient fields ($\times .01$) for the Atlantic south-of-ridge fast V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

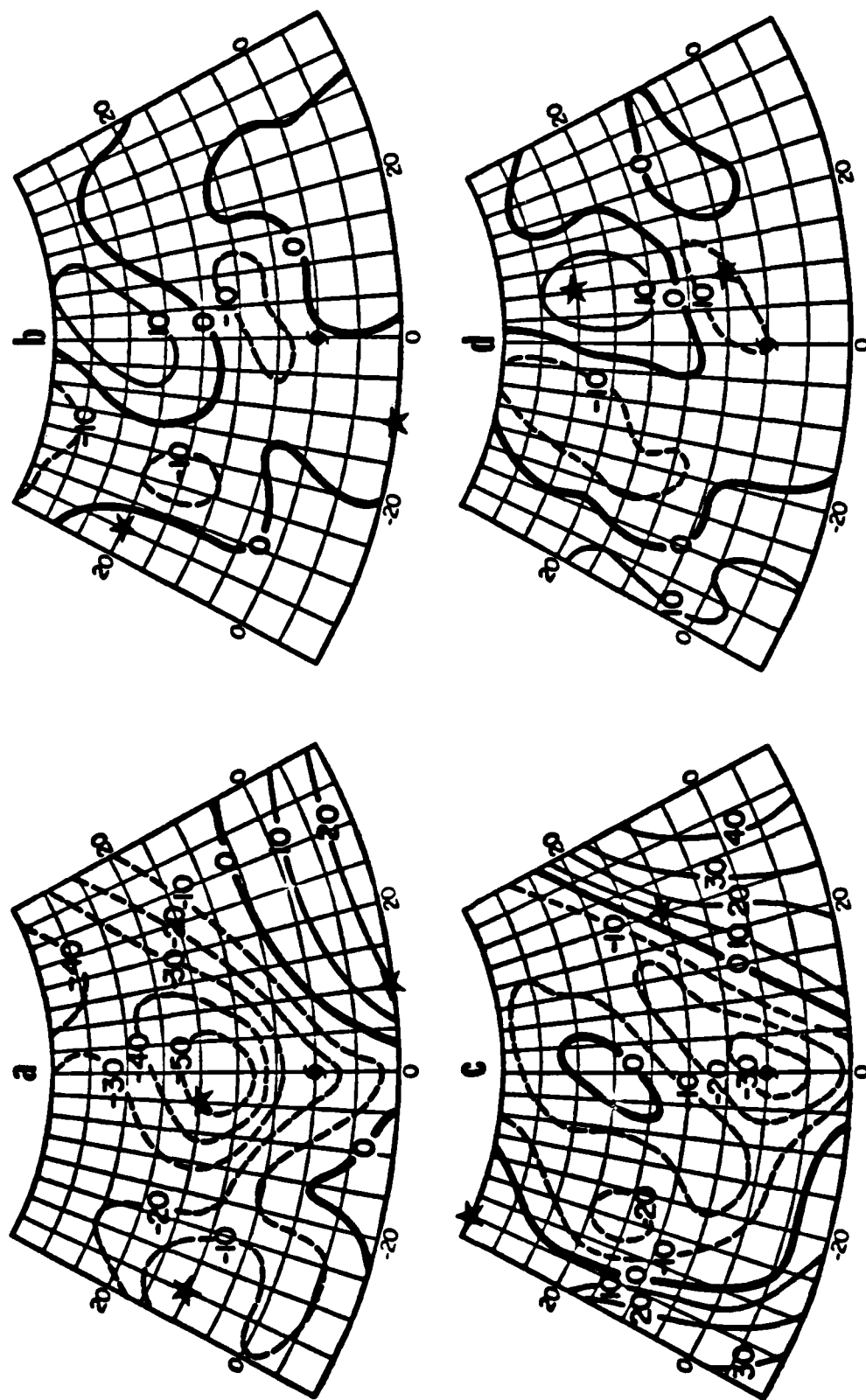


Fig. B.7. Correlation coefficient fields ($\times .01$) for the Atlantic south-of-ridge slow U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

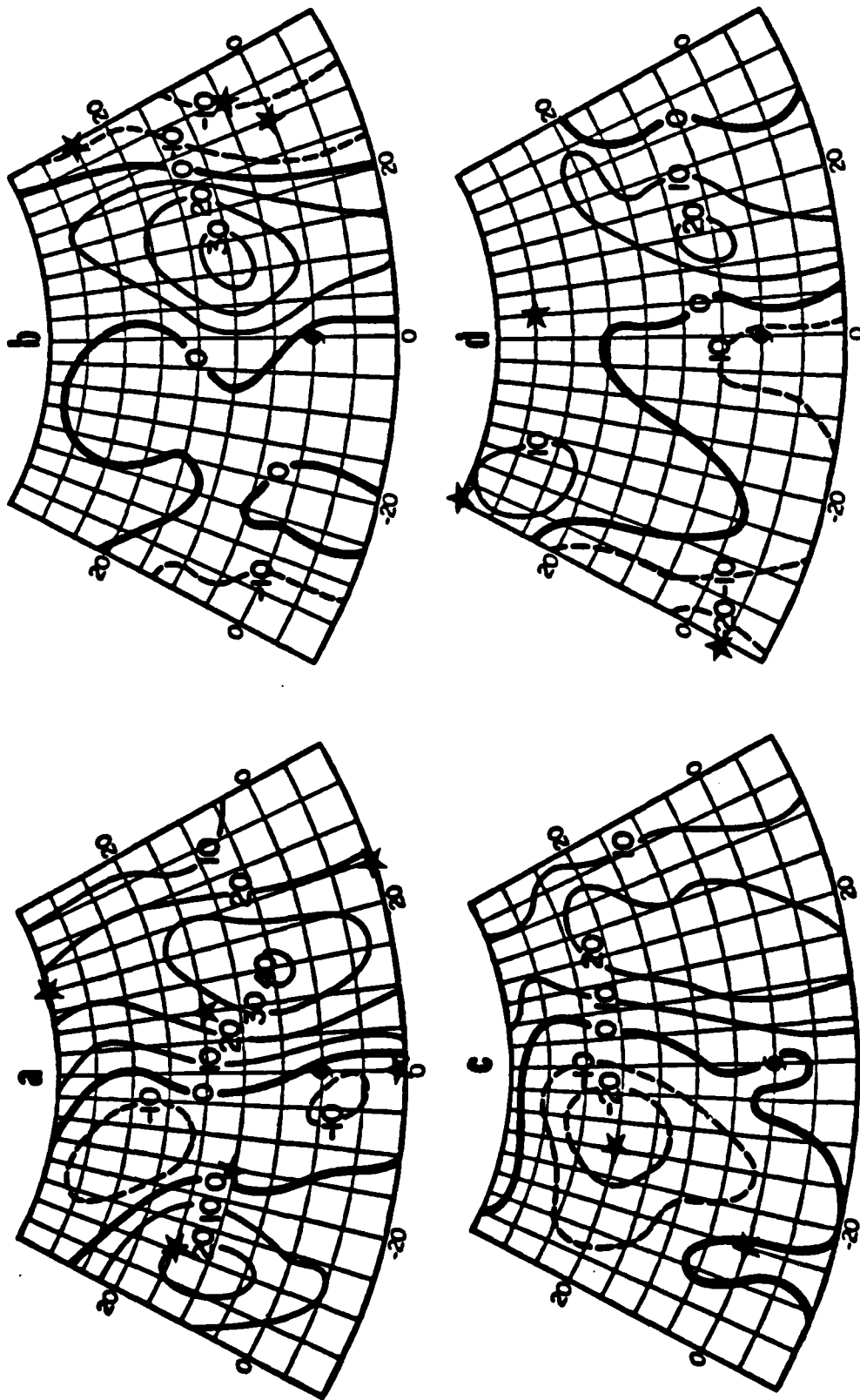


Fig. B.8. Correlation coefficient fields ($\times .01$) for the Atlantic south-of-ridge slow V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\odot) and the stars indicate the gridpoints at which predictors were selected.

APPENDIX C

Correlation coefficients fields for the NW Pacific on-the-ridge and south-of-ridge categories.

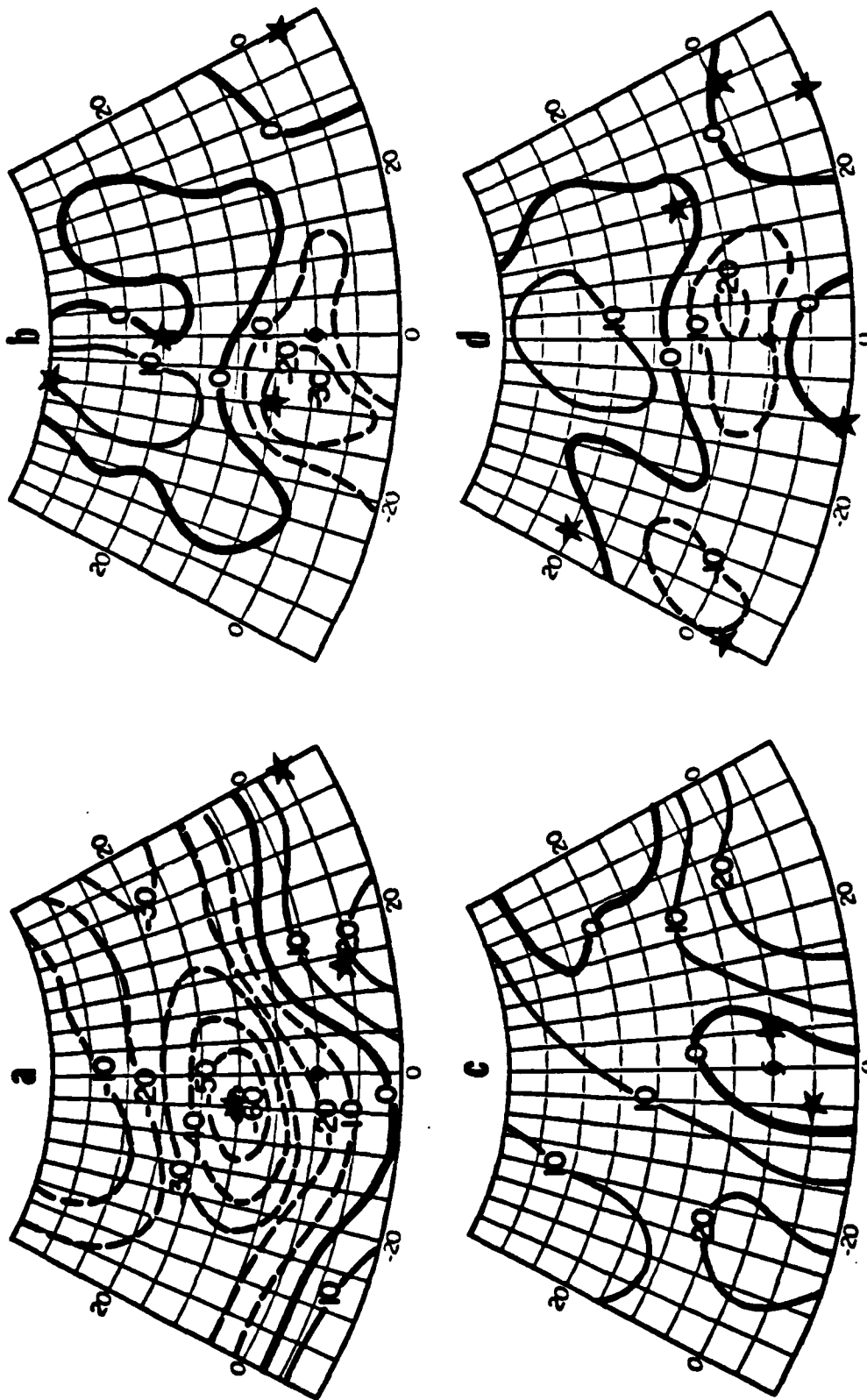


Fig. C.1. Correlation coefficient fields ($\times .01$) for the NW Pacific on-the-ridge fast U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\bullet) and the stars indicate the gridpoints at which predictors were selected.

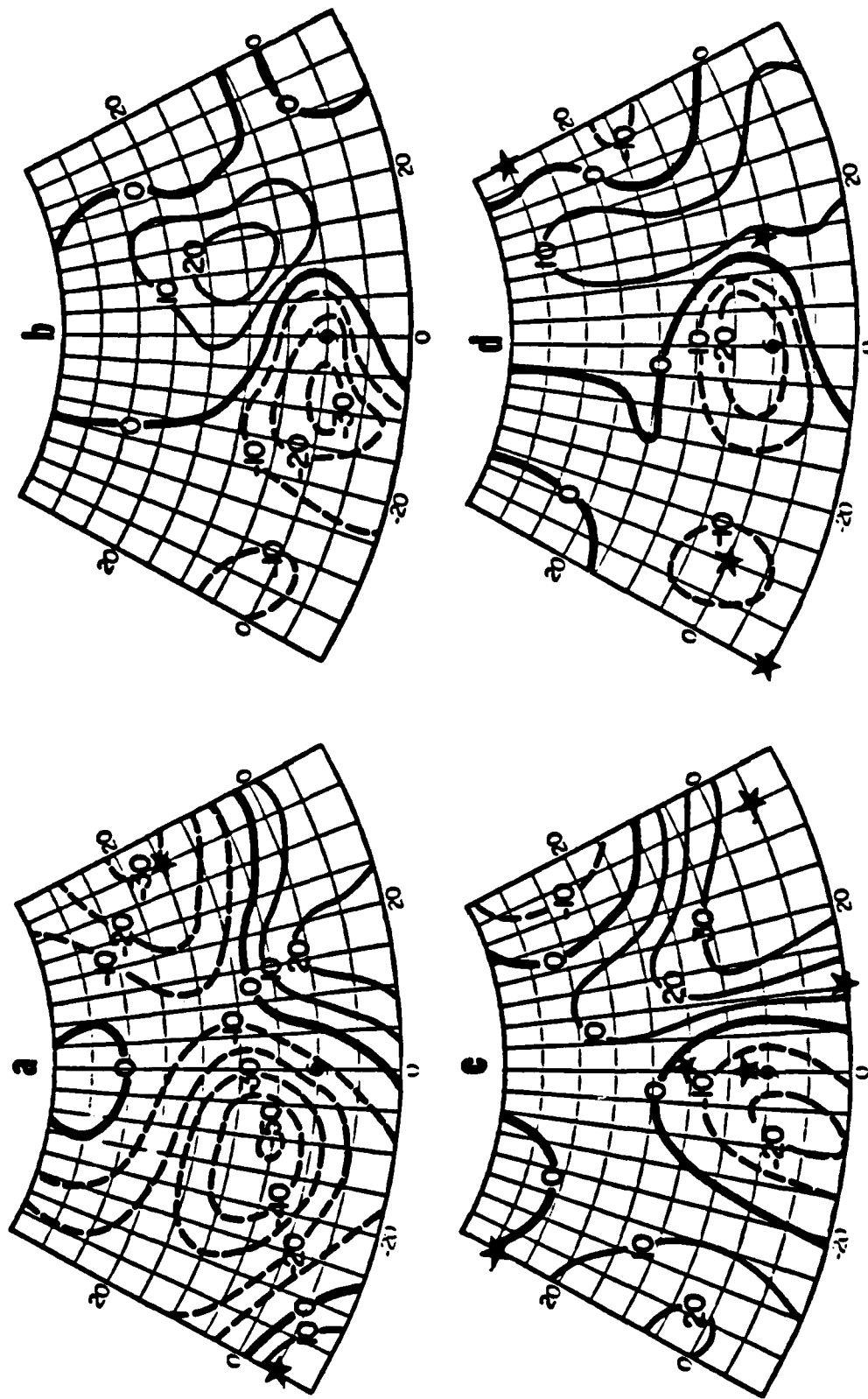


Fig. C.2. Correlation coefficient fields ($\times .01$) for the NW Pacific on-the-ridge fast V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\star) and the stars indicate the gridpoints at which predictors were selected.

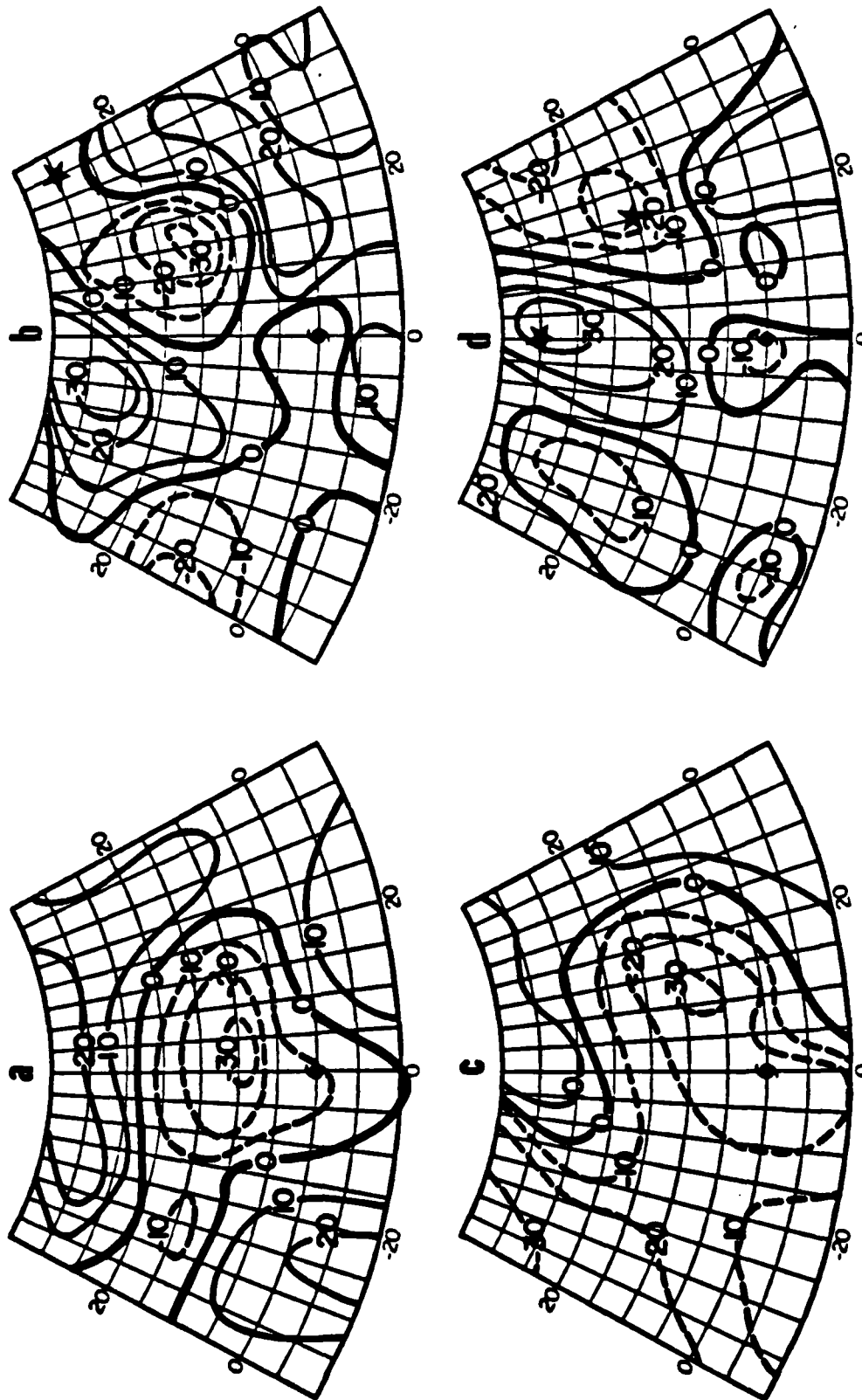


Fig. C.3. Correlation coefficient fields ($\times .01$) for the NW Pacific on-the-ridge slow U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (*) and the stars indicate the gridpoints at which predictors were selected.

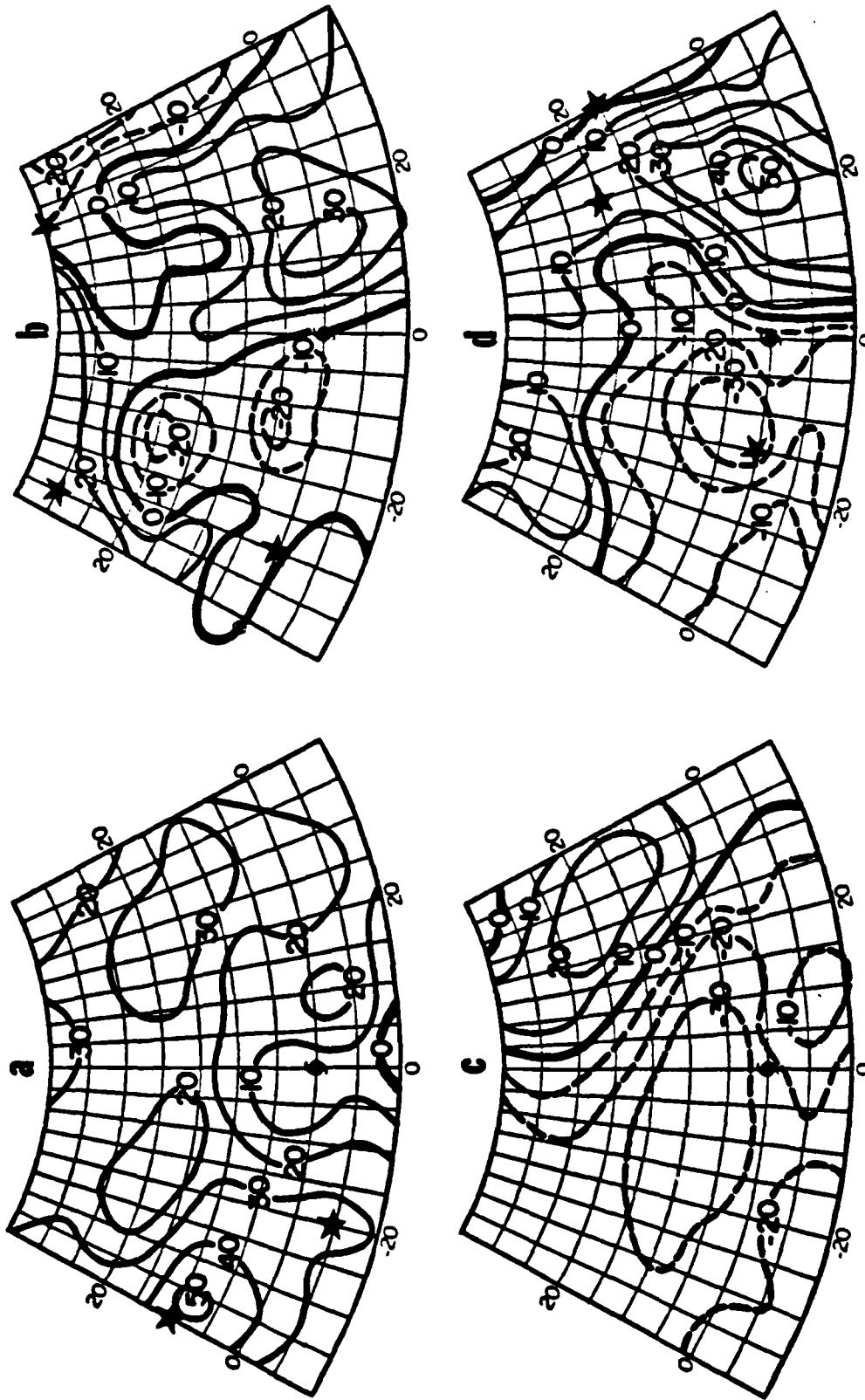


Fig. C.4. Correlation coefficient fields ($\times .01$) for the NW Pacific on-the-ridge slow V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (*) and the stars indicate the gridpoints at which predictors were selected.

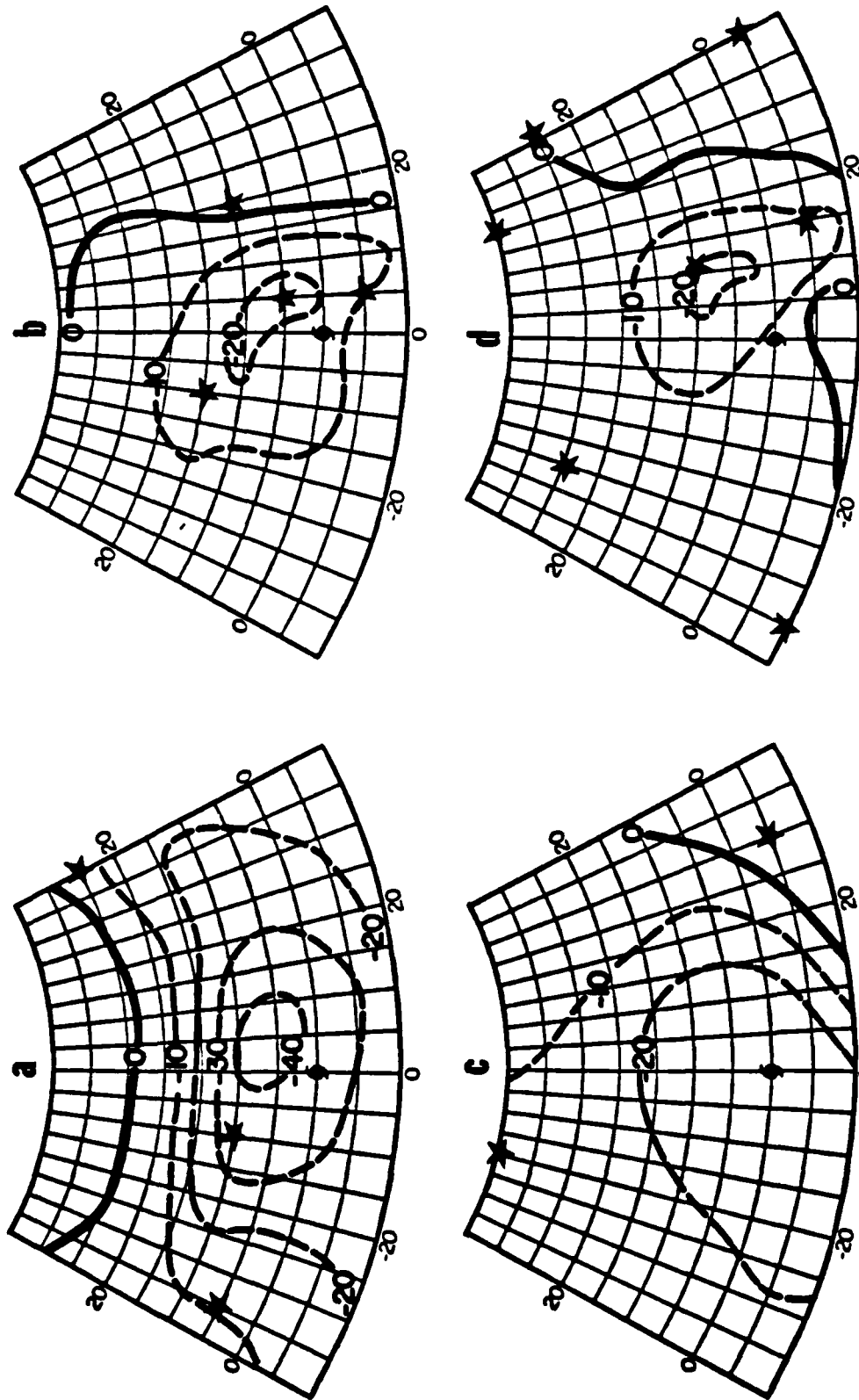


Fig. C.5. Correlation coefficient fields ($\times .01$) for the NW Pacific south-of-ridge fast U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (\bullet) and the stars indicate the gridpoints at which predictors were selected.

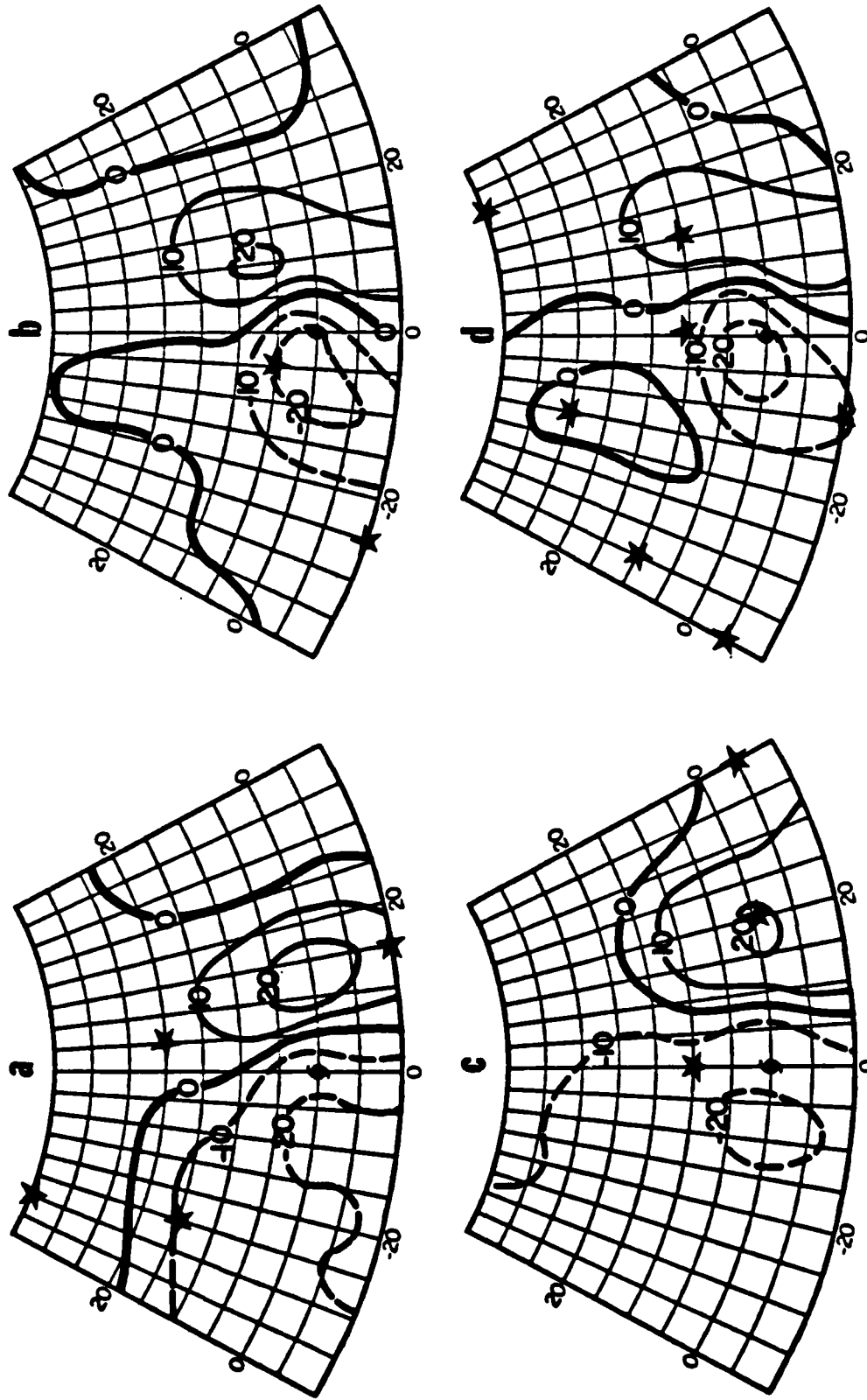


Fig. C.6. Correlation coefficient fields ($\times .01$) for the NW Pacific south-of-ridge fast V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (●) and the stars indicate the gridpoints at which predictors were selected.

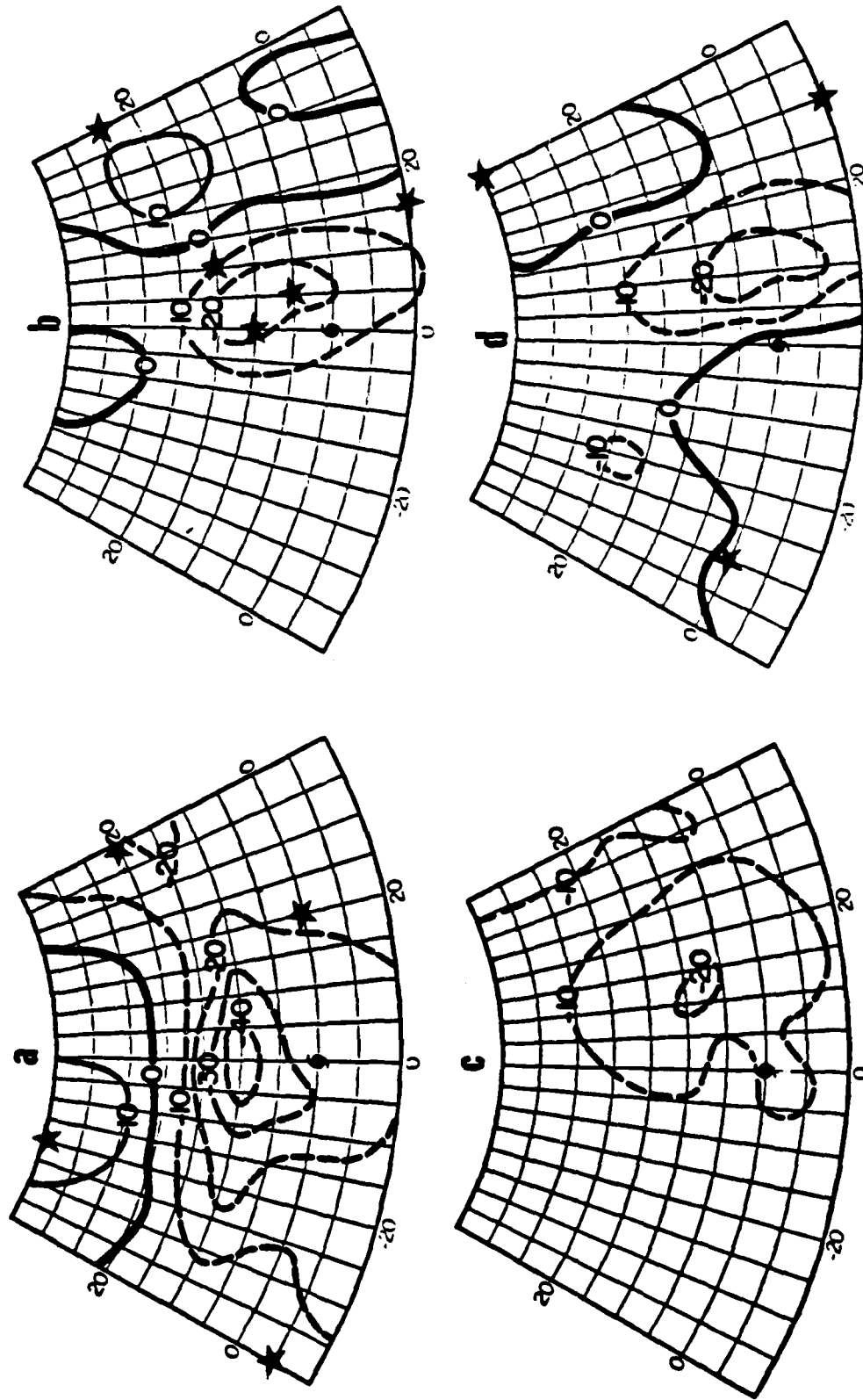


Fig. C.7. Correlation coefficient fields ($\times .01$) for the NW Pacific south-of-ridge slow U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (●) and the stars indicate the gridpoints at which predictors were selected.

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A STATISTICAL METHOD FOR ONE-TO THREE-DAY TROPICAL
CYCLONE TRACK PREDICTION(U) AIR FORCE INST OF TECH
WRIGHT-PATTERSON AFB OH C R MATSUMOTO 1984

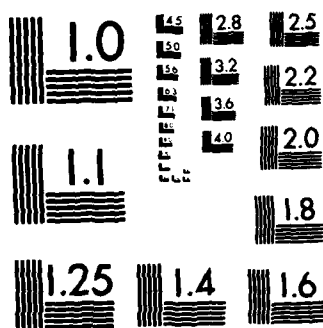
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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

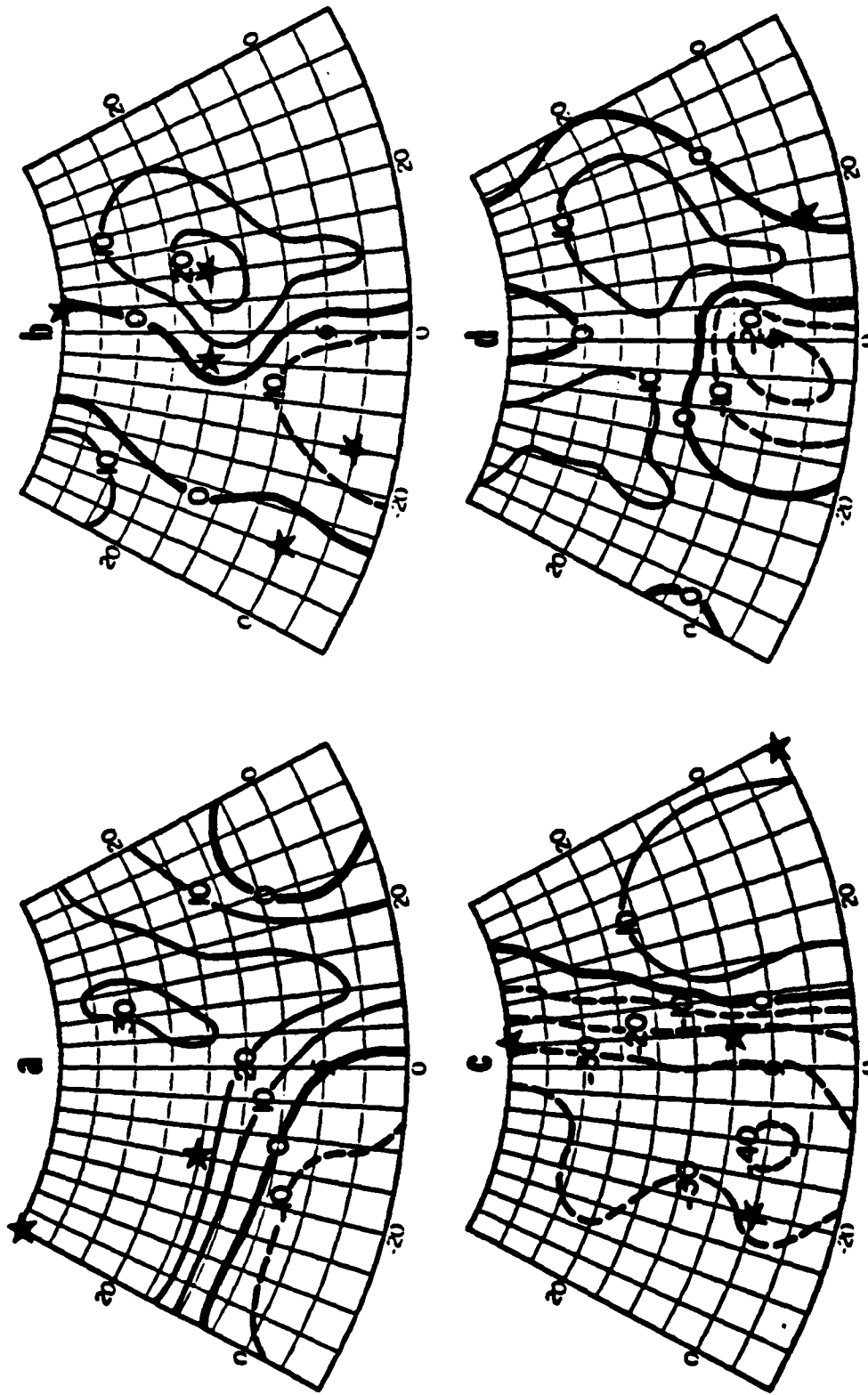


Fig. C.8. Correlation coefficient fields ($\times .01$) for the NW Pacific south-of-ridge slow V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (*) and the stars indicate the gridpoints at which predictors were selected.

APPENDIX D

Correlation coefficients fields for the North Indian Ocean on-the-
ridge and south-of-ridge categories.

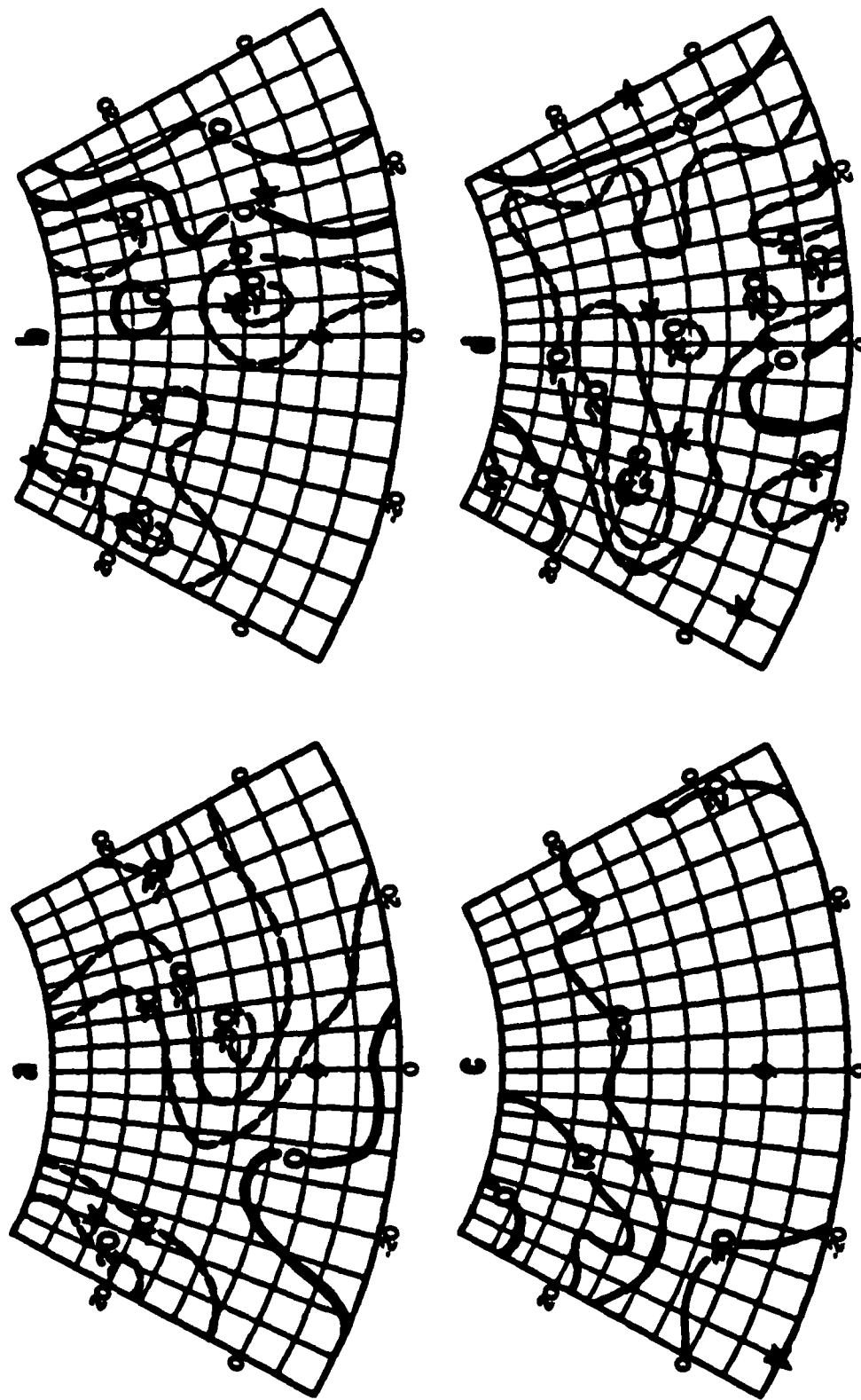


Fig. D.1. Correlation coefficient fields ($\alpha = 0.1$) for the North Indian Ocean on-the-ridge U motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (ϕ) and the stars indicate the gridpoints at which predictors were selected.

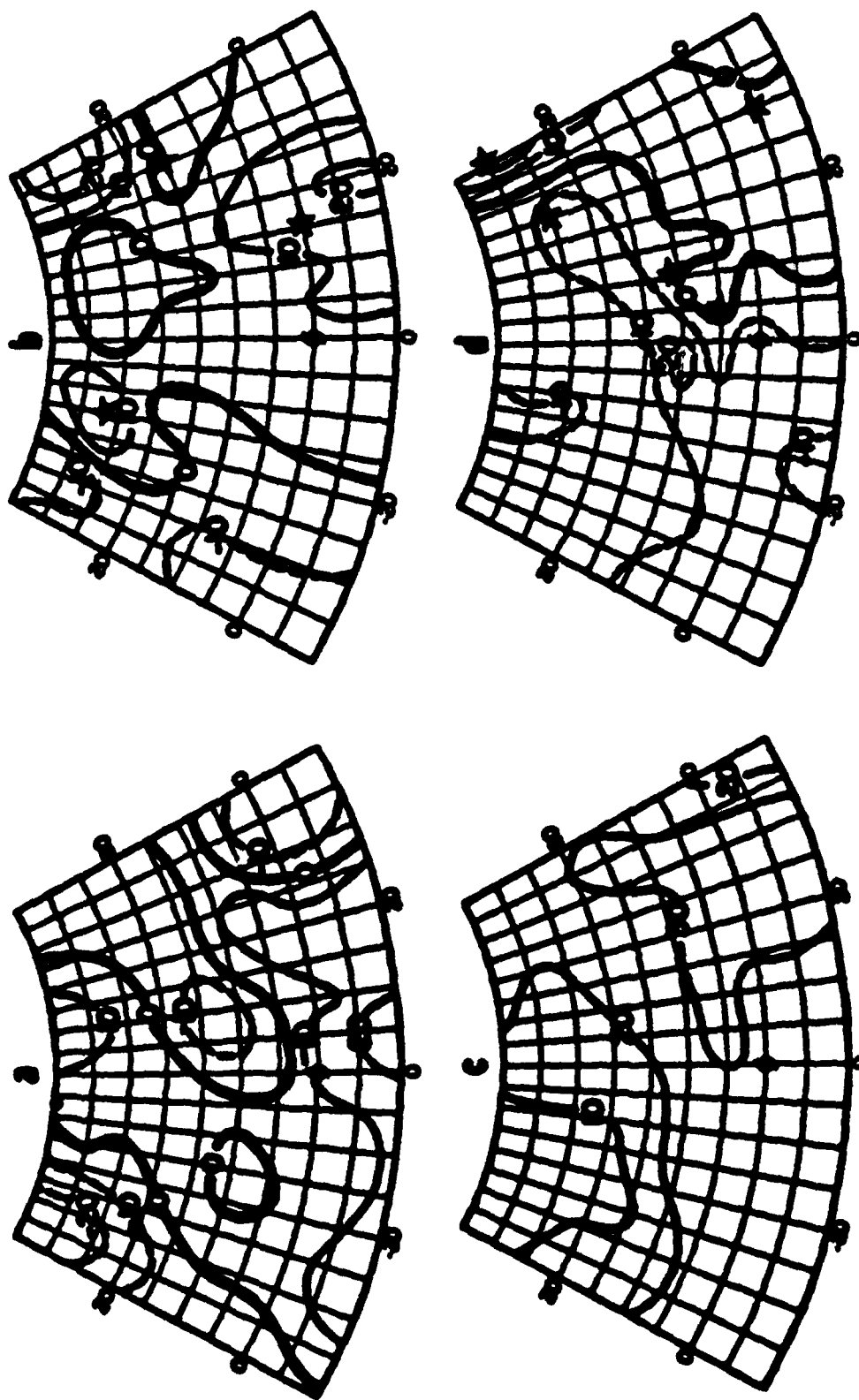


Fig. D.2. Correlation coefficient fields (x, y) for the North Indian Ocean on-the-ridge V motion. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (0) and the stars indicate the gridpoints at which predictors were selected.

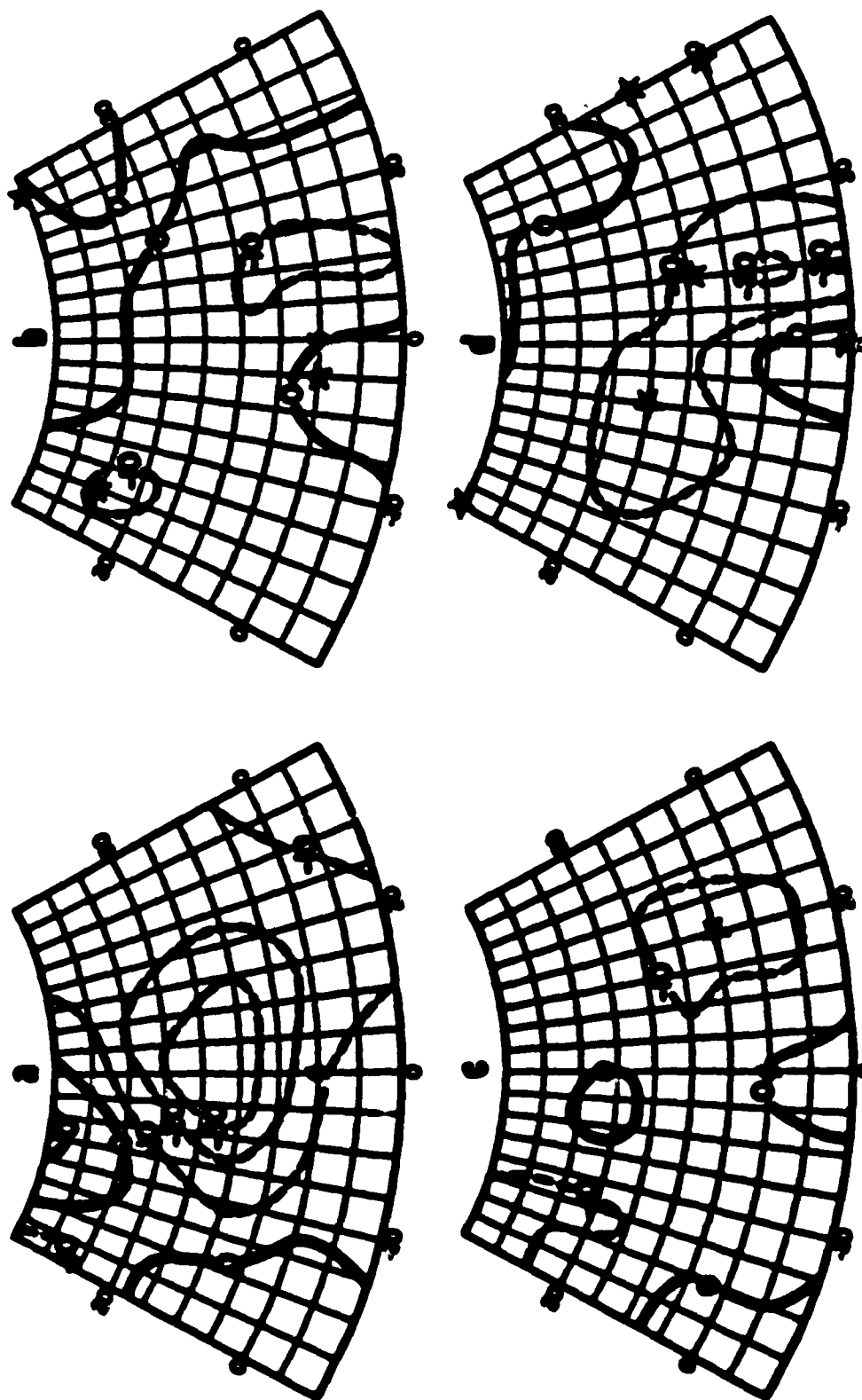


Fig. B.3. Correlation coefficient fields ($\alpha = 0.1$) for the North Indian Ocean south-of-ridge region. The four panels present the correlation between cyclone motion and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Northward and eastward cyclone motions are positive. The position of the cyclone is denoted by (•) and the stars indicate the gridpoints at which predictors were selected.

APPENDIX E

OPERATIONAL IMPLEMENTATION

The attractiveness of a statistical-dynamical prediction model such as this is the ease with which it can be applied directly at operational locations and aboard ships without a link to a large computer data base.

The basic design concept of the new model is simple enough such that a forecaster could generate the 24-, 48-, and 72-hour forecast positions with the use of a desk-top calculator.

The only information required as input for the model are the current, past 12-hour and past 24-hour positions of the cyclone and the current surface, 500 mb and 200 mb charts plus the 24- and 48-hour surface, 500 mb and 200 mb forecast fields. These forecast fields could be subjectively made by the forecaster for the specific areas where predictor values are required.

For the NW Pacific, South China Sea, and North Indian Oceans, the regression equations with 500 mb steering and no speed stratification should be used. The regression equations with 200 mb steering should only be used for strong typhoons (≥ 90 kts) undergoing recurvature in the NW Pacific. For the Atlantic, the regression equations with 200 mb steering and no speed stratification should be used.

Basically, one always starts with the 500 mb height field to determine the position of the cyclone relative to the subtropical ridge (south, east, or north). Then select the appropriate regression equations (one for north-south displacement, a second for east-west displacement)

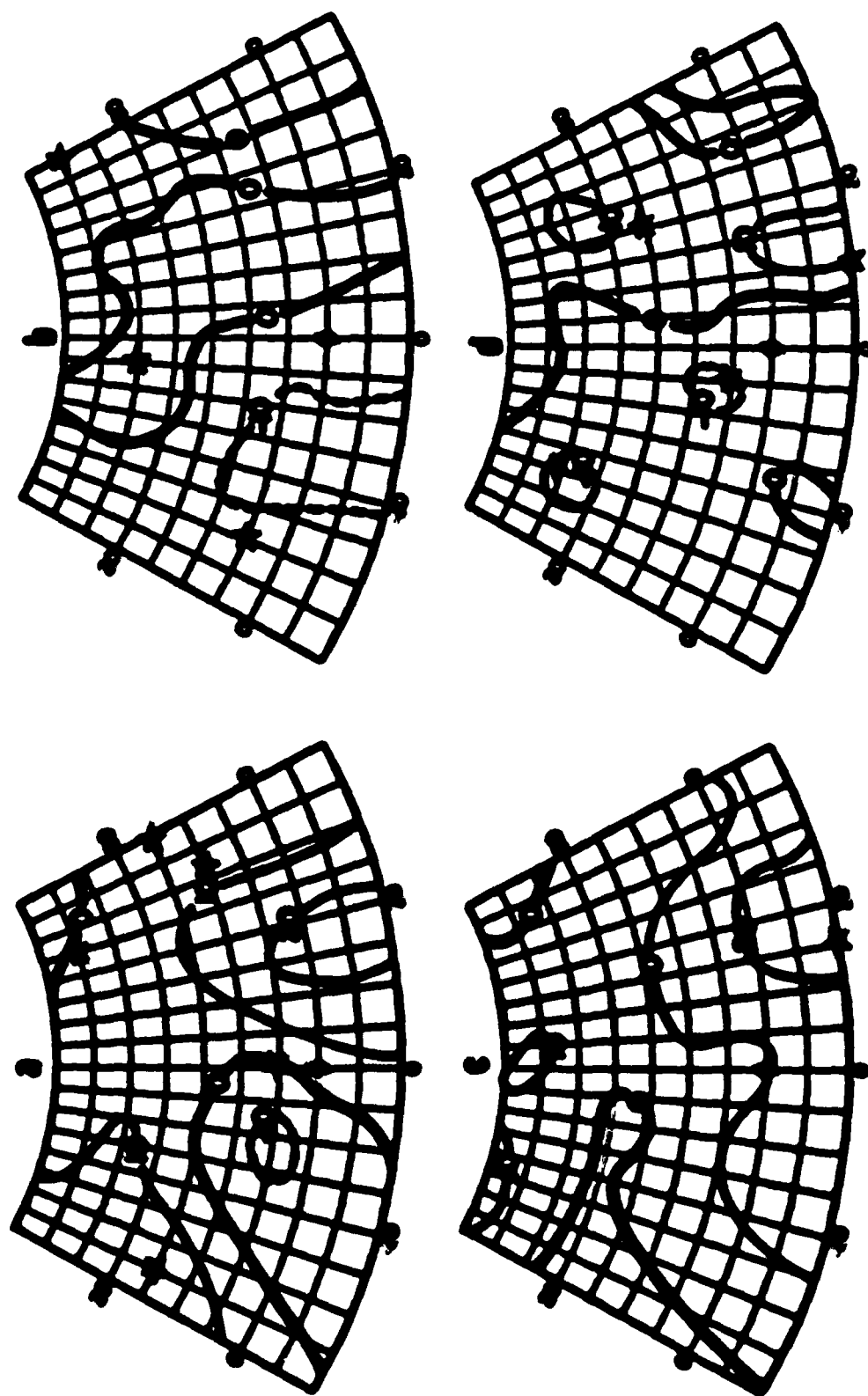


Fig. 9.4. Correlation coefficient fields (a, b) for the North Indian Ocean south-of-ridge V section. The four panels present the correlation between cyclone section and (a) 500 mb height; (b) 24-hour change of the 500 mb height; (c) sea level pressure; and (d) 24-hour change of sea level pressure. Inward and outward cyclone sections are positive. The position of the cyclone is denoted by (c) and the stars indicate the gridpoints at which predictors were selected.

and determine the predictors required. If one or more of the predictors is past motion, compute it as follows:

north-south displacement Y is given by

$$1111.949 \times (LAT_c - LAT_p) / HOUR$$

where LAT_c is the current latitude

LAT_p is the previous latitude either 12 or 24 hours earlier

HOUR is 12 or 24 depending on whether a 12-hour past motion or 24-hour past motion is being computed.

east-west displacement X is given by:

$$1111.949 \times \cos [(LAT_c + LAT_p) / 2] \times (LON_c - LON_p) / HOUR$$

where LAT_c is the current latitude

LAT_p is the previous latitude either 12 or 24 hours earlier

LON_c is the current longitude

LON_p is the previous longitude either 12 or 24 hours earlier

HOUR is 12 or 24 depending on whether a 12-hour or 24-hour past motion is being computed

In computing the past 12-hour motion at the 24- and 48-hour forecast positions, a position halfway between the forecast position and the position 24 hours earlier is used as the 12-hour old position.

If the required predictor is 999 mb height or sea level pressure, go to the appropriate chart and estimate the value at the proper gridpoint from the cyclone. If the forecast pressure is at the initial position, the chart to use would be the current analysis. If the pressure is at the 24-hour forecast position, the chart to use is the 24-hour prognostic field valid at the time of the 24-hour position. If the forecast pressure is at the 48-hour forecast position, the chart to use is the 48-hour prog field valid at the time of the 48-hour position.

If the required predictor is the tendency of the 500 mb height or sea level pressure, i.e., the 24-hour change in the height or pressure, two charts are required. If the forecast process is at the initial position, the charts to use are the current analysis and the 24-hour old analysis. If the process is at the 24-hour forecast position, the charts to use are the 24-hour prog field valid at the time of the 24-hour position and the initial analysis. If the process is at the 48-hour forecast position, the charts to use are the 48-hour prog field valid at the time of the 48-hour position and the 24-hour prog valid at the time of the 24-hour position. In this way, one is only using "current" analysis and previous 24-hour changes, never looking ahead at any "prog" fields.

The synoptic and steering predictors are always computed relative to the "current" cyclone position. The steering predictors are computed differently depending on whether the steering is being computed over the cyclone or away from the cyclone center. For steering over the cyclone, the five nearest gridpoints 10° away from the center on either side are averaged and then subtracted to provide a gradient across the cyclone. For steering away from the cyclone, a single gridpoint 5° either side of the point for which the steering is being computed is used. For the exact gridpoints, refer to Chapter 3.

In the development of the regression equations, geostrophic winds were computed from the gradient of geopotential heights for the steering predictors rather than using actual observed winds. If, in an operational setting, it is preferable to use the observed winds rather than computing the winds from the height gradient, the only conversion required is to multiply the U and V components (in m/s) by 9.8 s^{-1} . This

conversion is required since the 2θ and the ΔX , ΔY terms from the geostrophic wind equation were not used to compute the regression coefficients for the steering predictors.

Following each of the first two 24-hour displacements, a category change relative to the subtropical ridge may be required. This can be done either objectively by noting the direction of motion (DOM) between the new forecast position and the position 24 hours earlier or subjectively by noting if the forecast position is approaching the subtropical ridge axis. If the objective method is used, for cyclones in the south-of-ridge category, a change to on-the-ridge category should be made if the DOM is between 330° and 30° and a change to north-of-ridge category should be made if the DOM is greater than 30° . Likewise, for cyclones in the on-the-ridge category, a change to north-of-ridge category should be made if the DOM is greater than 30° . For cyclones north of the ridge, no category change is necessary. Although the use of a blend zone was never tested, for cases with DOM between 330° and 330° or if the choice between two categories is not clear-cut, both the south-of-ridge equation and on-the-ridge equation may be used to compute an average position between the two.

The formula for computing the 24-hour displacement to determine the forecast position is given by:

$$\text{NEWLAT} = (1/C_0 + \sum_{i=1}^n C_i P_i) (24) / 1111.949 = \text{GLAT}$$

$$\text{NEWLON} = (1/C_0 + \sum_{i=1}^n C_i P_i) (24) / (1111.949 \pm \cos(\text{NEWLAT} - \text{GLAT})) = \text{GLON}$$

where NEWLAT is the forecast latitude

GLAT is the forecast minus 24-hour latitude

NEWLON is the forecast longitude

GLON is the forecast minus 24-hour longitude

C_0 is the intercept

C_n are the n regression coefficient

P_n are the n predictor values

The actual procedure for computing one 24-hour segment of a 72-hour forecast will be presented as an example. The example is the forecast situation for Supertyphoon Wynne on October 11, 1980 at 1200 GMT. The track for Wynne is shown in Fig. E.1. Table E.1 contains the 900 mb geopotential heights at the 17×10 gridpoints at warning time T_0 and at T_0 minus 24 hours. Similarly, Tables E.2 and E.3 contain the sea level pressures and the 200 mb heights, respectively. Figure E.2 is the JTWC hand-drawn streamline analysis at the 900 mb level for 1200 GMT on October 11. Based on the 1200 GMT analysis, the cyclone should be placed in the on-the-ridge category. Applying the regression equation for the north-south displacement for on-the-ridge category, the first predictor is the past 12-hour north-south motion. The initial cyclone position is 23.6°N 127.2°E . The past 12-hour position is 22.6°N 128.8°E . The past 12-hour north-south displacement is computed as:

$$Y = 1111.949 \pm (23.6 - 22.6) / 12 \\ = 111.1949$$

Multiplying this displacement by its coefficient 0.933 results in a contribution of 99.3449.

The second predictor is the 900 mb height 5° north and 10° west of the cyclone center. From Table E.1, this height is 9861 m. Multiplying this height by its coefficient $- .8772$ results in a contribution of -9238.4892 .

Similarly, predictors (3) through (2) results in:

$$(3) \text{ pressure } 40^\circ \text{ east of cyclone} = 1013 \pm 3.9989 = 4038.8833$$

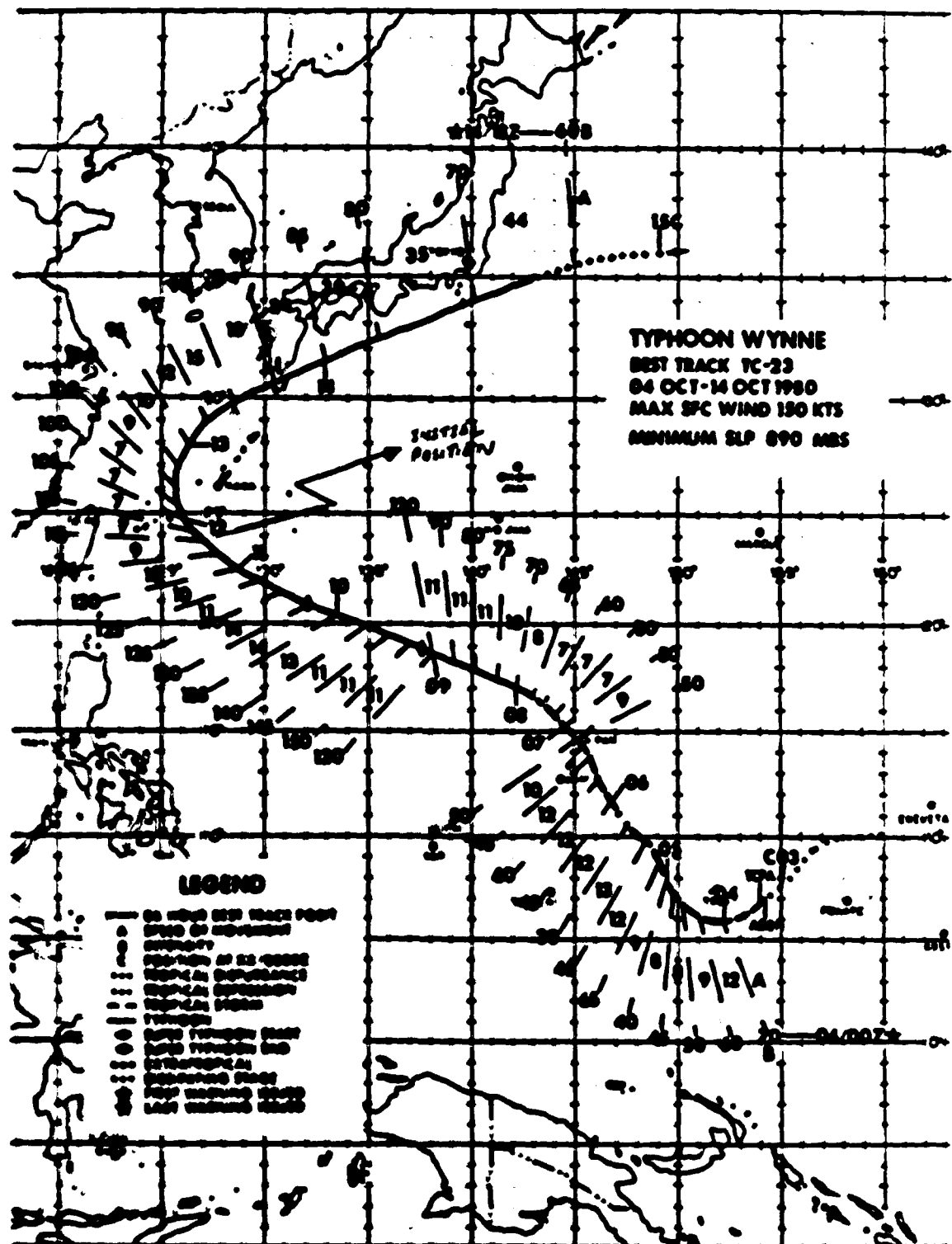


TABLE E.2

Panel A contains the current (October 11 1200GMT) sea level pressures (mb) at the 17 x 10 gridpoints relative to the cyclone center. The cyclone is located at the gridpoint indicated by a box. Panel B contains the 24-hour old (October 10 1200GMT) sea level pressures at the 17 x 10 gridpoints relative to the cyclone center. The grid is 5° x 5°.

A																
1029.	1029.	1029.	1027.	1026.	1025.	1024.	1023.	1021.	1017.	1012.	1006.	1001.	997.	993.	990.	988.
1033.	1030.	1030.	1030.	1028.	1025.	1024.	1023.	1023.	1019.	1012.	1006.	1002.	1000.	998.	997.	998.
1027.	1024.	1024.	1023.	1022.	1021.	1020.	1018.	1016.	1013.	1012.	1014.	1012.	1010.	1008.	1008.	1011.
1026.	1024.	1024.	1023.	1022.	1021.	1020.	1018.	1016.	1013.	1012.	1014.	1012.	1010.	1008.	1017.	1019.
1019.	1016.	1016.	1015.	1014.	1013.	1012.	1010.	1008.	1005.	1003.	1001.	1001.	1014.	1016.	1018.	1020.
1014.	1011.	1011.	1010.	1009.	1008.	1007.	1005.	1003.	1001.	1001.	1013.	1011.	1014.	1016.	1017.	1020.
1007.	1004.	1004.	1003.	1002.	1001.	1000.	1000.	1000.	1000.	1012.	1010.	1011.	1011.	1013.	1013.	1015.
1007.	1007.	1007.	1006.	1005.	1004.	1003.	1002.	1001.	1000.	1012.	1010.	1010.	1010.	1012.	1013.	1014.
1008.	1007.	1007.	1006.	1005.	1004.	1003.	1002.	1001.	1000.	1011.	1011.	1010.	1010.	1011.	1012.	1012.
B																
1035.	1032.	1030.	1029.	1028.	1027.	1025.	1024.	1021.	1017.	1009.	998.	992.	986.	981.	978.	978.
1033.	1031.	1029.	1028.	1027.	1026.	1025.	1024.	1023.	1016.	1009.	1002.	998.	995.	992.	990.	992.
1027.	1024.	1024.	1023.	1022.	1021.	1020.	1018.	1015.	1013.	1013.	1016.	1016.	1017.	1018.	1021.	1022.
1026.	1024.	1024.	1023.	1022.	1021.	1020.	1018.	1015.	1013.	1013.	1016.	1016.	1017.	1018.	1021.	1022.
1018.	1015.	1014.	1013.	1012.	1011.	1010.	1008.	1005.	1003.	1003.	1013.	1011.	1014.	1016.	1022.	1023.
1014.	1011.	1010.	1009.	1008.	1007.	1006.	1005.	1004.	1003.	1013.	1011.	1011.	1012.	1014.	1020.	1020.
1010.	1007.	1006.	1005.	1004.	1003.	1002.	1001.	1000.	1000.	1012.	1010.	1011.	1011.	1013.	1019.	1014.
1008.	1007.	1006.	1005.	1004.	1003.	1002.	1001.	1000.	1000.	1012.	1010.	1011.	1011.	1013.	1019.	1014.
1008.	1007.	1006.	1005.	1004.	1003.	1002.	1001.	1000.	1000.	1012.	1010.	1011.	1011.	1013.	1019.	1014.

TABLE E.3

Panel A contains the current (October 11 1200GMT) 200 mb geopotential heights (m) at the 17 x 10 gridpoints relative to the cyclone center. The cyclone is located at the gridpoint indicated by a box. Panel B contains the 24-hour old (October 10 1200GMT) 200 mb geopotential heights at the 17 x 10 gridpoints relative to the cyclone center. The grid is 5° x 5°.

A																
11727.	11626.	11838.	11520.	11507.	11496.	11407.	11412.	11357.	11321.	11318.	11316.	11323.	11323.	11316.	11309.	11333.
11744.	11643.	11551.	11494.	11485.	11507.	11498.	11452.	11405.	11369.	11365.	11359.	11363.	11363.	11354.	11371.	11441.
11780.	11693.	11606.	11565.	11593.	11635.	11635.	11603.	11553.	11524.	11510.	11524.	11512.	11512.	11524.	11543.	11643.
11809.	11812.	11761.	11758.	11814.	11881.	11902.	11893.	11862.	11838.	11831.	11851.	11840.	11840.	11851.	11886.	11922.
12062.	12021.	11998.	12011.	12118.	12161.	12190.	12208.	12267.	12194.	12189.	12189.	12197.	12197.	12189.	12192.	12196.
12308.	12208.	12321.	12253.	12339.	12372.	12393.	12411.	12415.	12407.	12402.	12399.	12399.	12399.	12390.	12361.	12340.
12321.	12350.	12377.	12408.	12440.	12454.	12469.	12483.	12489.	12489.	12478.	12462.	12462.	12462.	12450.	12435.	12357.
12418.	12441.	12452.	12456.	12465.	12464.	12472.	12485.	12490.	12499.	12482.	12467.	12467.	12467.	12462.	12447.	12376.
12434.	12443.	12452.	12456.	12465.	12464.	12467.	12479.	12490.	12499.	12476.	12460.	12460.	12460.	12457.	12448.	12396.
12431.	12445.	12451.	12454.	12461.	12460.	12463.	12471.	12479.	12479.	12469.	12460.	12460.	12460.	12457.	12448.	12396.
B																
11675.	11586.	11530.	11502.	11474.	11458.	11435.	11403.	11358.	11326.	11320.	11319.	11319.	11319.	11315.	11318.	11367.
11646.	11574.	11522.	11517.	11538.	11545.	11534.	11490.	11435.	11383.	11368.	11348.	11348.	11348.	11338.	11346.	11420.
11706.	11661.	11622.	11604.	11649.	11659.	11660.	11656.	11640.	11622.	11602.	11597.	11597.	11597.	11585.	11580.	11612.
11826.	11815.	11807.	11802.	11860.	11865.	11888.	11902.	11926.	11944.	11939.	11904.	11904.	11904.	11869.	11871.	11914.
11998.	12021.	12047.	12072.	12138.	12176.	12178.	12187.	12211.	12236.	12228.	12199.	12199.	12199.	12178.	12167.	12187.
12184.	12222.	12259.	12293.	12349.	12376.	12392.	12404.	12419.	12423.	12405.	12380.	12380.	12380.	12359.	12318.	12343.
12334.	12362.	12393.	12428.	12451.	12462.	12474.	12479.	12488.	12487.	12471.	12455.	12455.	12455.	12439.	12415.	12418.
12427.	12442.	12459.	12464.	12470.	12476.	12474.	12487.	12500.	12503.	12484.	12462.	12462.	12462.	12458.	12449.	12408.
12433.	12446.	12455.	12460.	12465.	12465.	12469.	12470.	12479.	12480.	12470.	12459.	12459.	12459.	12456.	12449.	12426.

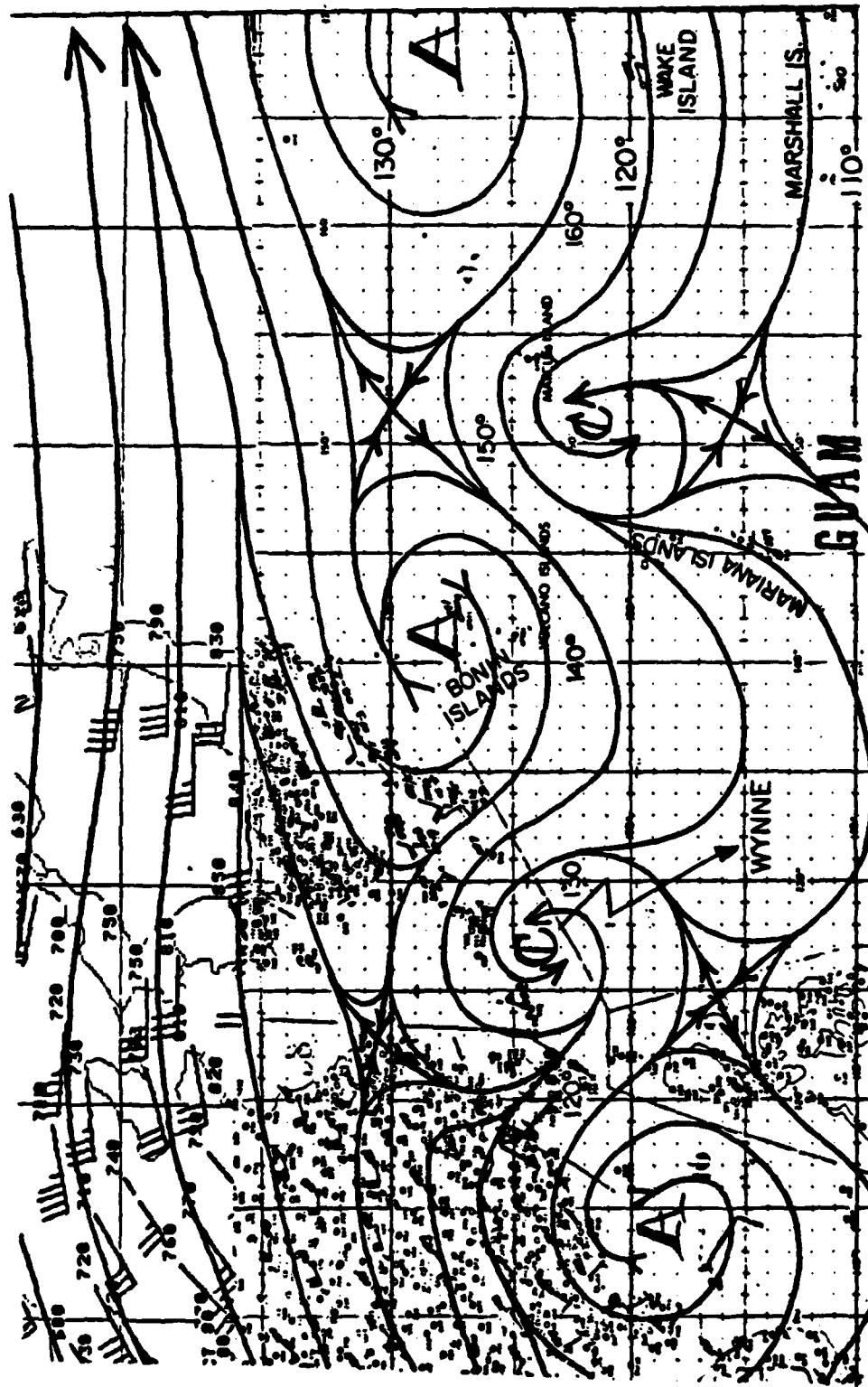


Fig. E.2. JWC hand-drawn 500 mb streamline analysis for 1200 GMT on October 11. Typhoon Wynne is located at 23.8°N 127.2°E or approximately 300 n mi. east of Taiwan at this time.

- (4) 24-hour pressure change 10° south 10° west of cyclone =
 $(1009-1010) \times -8.2569 = 8.2569$
- (5) pressure 10° south of cyclone = $1006 \times 3.4909 = 3511.8454$
- (6) 24-hour pressure change 20° north 5° west of cyclone =
 $(1027-1024) \times -1.4298 = -4.2894$
- (7) 24-hour height change 15° north 25° west of cyclone =
 $(5742-5754) \times -.2148 = 2.5776$
- (8) 24-hour pressure change 5° north 15° east of cyclone =
 $(1016-1017) \times 4.6907 = -4.6907$
- (9) pressure 5° north 5° west of cyclone = $1015 \times -3.9711 =$
 -4030.6665
- (10) height 10° south 40° west of cyclone = $5844 \times .2906 =$
 1698.2664
- (11) past 24-hour east-west motion = $1111.949 \times \cos [(21.5 + 23.8)/2] \times$
 $(127.2-130.8)/24 = -153.9284 \times -.1238 = 19.0563$
- (12) 24-hour height change 30° north 5° east of cyclone =
 $(5363-5329) \times -.1294 = -4.3996$
- (13) pressure 20° east of cyclone = $1011 \times 4.7028 = 4654.5308$
- (14) 24-hour pressure change 15° north 40° west of cyclone =
 $(1018-1018) \times 1.6751 = 0$
- (15) 24-hour height change 15° north 20° east of cyclone =
 $(5763-5777) \times -.1196 = 1.6744$
- (16) 24-hour height change 35° north 30° east of cyclone =
 $(5186-5161) \times -.0761 = -1.9025$

(17) 24-hour change of the north-south component of the 200 mb steering over the cyclone =

$$\begin{aligned} & [((12407+12489+12499+12489+12479)/5 - (12372+12454+12468+12464+12460)/5) / [\sin(23.8) \times \cos(23.8)] - [(12423+12487+12503+12491+12480)/5 - (12376+12462+12476+12470+12465)/5] / [\sin(23.8) \times \cos(23.8)]] \times .0498 \\ & = (78.5423 - 73.1256) \times .0498 = .2698 \end{aligned}$$

(18) 24-hour height change 35° north 30° west of cyclone =

$$(5471-5488) \times -.0844 = -1.4348$$

(19) 24-hour change of the east-west component of the 200 mb steering 10° north of cyclone =

$$\begin{aligned} & [(12483-12208)/\sin(33.8)] - [(12479-12187)/\sin(33.8)] \times -.0353 = \\ & 1.0787 \end{aligned}$$

(20) 24-hour pressure change 10° south 10° east of cyclone =

$$(1011-1011) \times -3.98 = 0$$

(21) Intercept = -4706.5091

Summing all of the contributions (103.3249) and adding it to the initial latitude results in a 24-hour forecast latitude of

$$[(103.3249 \times 24) / 1111.949] + 23.8 = 26.0$$

Applying the regression equation for the east-west displacement for the on-the-ridge category, the first predictor is the 500 mb height 10° north and 5° west of the cyclone center. From Table E.1, this height is 5842 m. Multiplying this height by its coefficient -.464 results in a contribution of -2710.688. The second predictor is the past 12-hour east-west motion. The initial cyclone position is $23.8^{\circ}\text{N } 127.2^{\circ}\text{E}$. The past 12-hour position is $22.6^{\circ}\text{N } 128.8^{\circ}\text{E}$. The past 12-hour east-west displacement is computed as:

$$X = 1111.949 \times \cos[(22.6 + 23.8)/2] \times (1272-128.8)/12 \\ = -136.3$$

Multiplying this displacement by its coefficient .302 results in a contribution of -41.163. Similarly, predictors (3) through (20) results in:

- (3) pressure 10° south of cyclone = $1006 \times 4.497 = 4523.982$
- (4) height 10° north 15° east of cyclone = $5871 \times -.261 = -1532.331$
- (5) 24-hour height change 5° north 10° west of cyclone = $(5861-5874) \times -.628 = 8.164$
- (6) 24-hour pressure change 25° north 35° west of cyclone = $(1029-1032) \times 1.53 = -4.59$
- (7) pressure 5° south 25° east of cyclone = $1011 \times 3.031 = 3064.341$
- (8) 24-hour pressure change 10° south 30° west of cyclone = $(1007-1008) \times 8.773 = -8.773$
- (9) height 40° east of cyclone = $5882 \times .349 = 2052.818$
- (10) 24-hour height change 10° south 10° west of cyclone = $(5859-5870) \times -.892 = 9.812$
- (11) 24-hour height change 30° north 15° west of cyclone = $(5474-5511) \times .114 = -4.218$
- (12) 24-hour pressure change 10° north 20° east of cyclone = $(1017-1022) \times -2.928 = 14.64$
- (13) pressure 30° north 25° east of cyclone = $1000 \times 1.92 = 1920$
- (14) past 24-hour north-south motion = $[1111.949 \times (23.8-21.5)/24] \times .183 = 19.5$
- (15) east-west component of the 200 mb steering over the cyclone =
$$[(12460+12463+12471+12479)/5 - (12372+12393+12411+12415+12407)/5] / \sin(23.8) \times .062 = 10.85$$
- (16) 24-hour pressure change 35° north 25° east of cyclone = $(997-986) \times -1.332 = -14.652$
- (17) height 35° west of cyclone = $5849 \times -.319 = -1863.831$
- (18) height 5° south 10° west of cyclone = $5866 \times -.369 = 2164.554$

(19) 24-hour height change 25° north 35° east of cyclone =
 $(5482-5389) \times -.059 = -.767$

(20) 24-hour height change 35° north 25° west of cyclone =
 $(5464-5468) \times -.091 = .364$

(21) Intercept = -7662.345

Summing all the contributions (-56.333) and adding it to the initial longitude results in a 24-hour forecast longitude of

$$(-56.333 \times 24) / 1111.949 \times \cos[(25.8 + 26.0)/2] + 127.2 = 125.9$$

In a manual mode, gridpoint data would not be available to the forecaster. Instead, he must use the available observations and estimate heights and pressures at the required gridpoints. To test the sensitivity of the regression equations, all of the required heights were either increased or decreased by 30 m from those that appear in Table E.1. Similarly, all of the pressures were either increased or decreased by 5 mb from those that appear in Table E.2. Neither the tendencies nor the steering predictors were altered since it was felt that 24-hour changes and height gradients are easier to estimate than the absolute values.

For the case of increasing all of the heights and pressures, the forecast latitude was half a degree further north and the forecast longitude nearly a degree further east, i.e., 26.5°N and 126.8°E . For the case of decreasing all of the heights and pressures, the forecast latitude was half a degree further south and the forecast longitude was one degree further west, i.e., 25.5°N and 125.0°E . Thus, the worst case situation of all the heights and pressures being too high or too low would 'add' approximately 60 n mi to the forecast position. Assuming that 30 m for the 500 mb height and 5 mb for the surface pressure are a

realistic range of values that a subjective analysis could vary from the gridpoint analysis, a 60 n mi difference in the forecast position would result.

Two points should be emphasized. The first is that relative to the verifying best track position, there is no way of knowing which forecast position is more accurate. The second is that the sensitivity test examined the worst case situation. In reality, some of the subjective estimation of synoptic values at specific gridpoints will be greater and some will be less than the gridpoint data. Hopefully, when all of them are summed, many of the erroneous high and the low values will cancel. The test was to provide a degree of 'alop' one could expect in the forecast position if subjective estimates for gridpoint values were used.

Obviously, in an automatic mode, no subjective estimation would be required. But again, one of the desirable features of a relatively simple model such as this is the opportunity for the forecaster to input the data with subjective quality control. If the synoptic values at gridpoints required by the model appear questionable, the forecaster could easily modify them to more realistic values. With the aid of a desk-top calculator, he/she could rerun the model several times with different predictor values to see the effect of the changes. Until the output from the global PE model improves, subjective modification of the forecast fields such as outlined here will probably be necessary.

A statistical-dynamical track prediction model is not currently available for use in the NW Pacific/South China Sea and North Indian

Concave. As shown by the verification of the model in Chapter 5, the potential for significant improvement exists with the use of this model.

END

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